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on Reliability and Quality Control

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THE IMPACT OF RELIABILITY REQUIREMENTS ON ORGANIZATION IN THE MANUFACTURE OF AIRBORNE ELECTRONIC EQUIPMENT

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The thesis of this paper, taken from data collected over the last four years (including the reliability experience data on Stromberg-Carlson's TACAN production run), is that reliability requirements have an impact on organization; that this impact is in the direction of adding functions, redefining functions, and changing or modifying structures; and that the changes in organization depend upon the past history of the company, its product line, its size, and the time in the development cycle that the reliability requirements are evaluated by management.

To define the terms of the title, "reliability requirements" is to be understood as meaning requirements contractually imposed by the customer with the purpose of insuring that the equipment or procured end item will have a designated numerical probability of failure-free or undegraded operation during a specified time interval under prescribed conditions of performance, environment, and operator skill. Reliability is a probability associated with a time function, whose limiting values are design parameters. "Airborne electronic equipment" is considered to be equipment carried either by a manned aircraft or by a guided missile. I have used the term "organization" to delineate the relationships among the people who carry out the various tasks incident to producing end items for a customer. It indicates their duties and responsibilities as specified by job descriptions and also the flow of authority in the decision-making process. Organization exists to enable a company to accomplish the basic mission in an efficient manner competitively with other companies similarly engaged.

I shall now demonstrate my thesis with case histories drawn chiefly from the various divisions of General Dynamics. First I'll take Stromberg-Carlson, but only briefly, because it's in the literature for those who are interested. Stromberg has basically a background as a supplier of electronic equipment. It is an old, well-established company with about 9,000 employees. They happened to be manufacturing TACAN at about the time that the Office of Secretary of Defense and Congress were investigating certain airborne electronic equipments which had been rushed into production as an aftermath of the Korean War. The disclosures relative to the reliability status of these equipments caused OSD to look critically at other equipments -- and there was TACAN! After an AGREE Committee made an investigation, extensive pressure was put on the Avionic Division, BuAer, and through that agency on each of the three contractors.

Stromberg did not have a reliability group per se at that time. Production was monitored by Quality Control, and when the bomb burst, Quality Control was expanded to cover a number of areas normally associated with reliability. Extensive testing was initiated, which meant procurement of expensive environmental test facilities. These extra facilities had to be placed under someone's control. In view of the fact that Quality Control was already monitoring the production and would be expected to perform the extended inspection, testing, selection of parts, and so forth, the environmental laboratory came under that group.

A similar decision was made with reference to the need for a failure-reporting and data-analyzing group, as well as the addition of numerous ad hoc committees set up to coordinate findings with the other contractors and to trouble-shoot specific problems. The result of being hit in the middle of a program, which was in production at the time, by the enhanced reliability requirements necessitated pursuing a path which would accomplish the mission as expeditiously and with as little disruption as possible. Since this solution solved the problem, as of today, the reliability efforts at Stromberg-Carlson remain under Quality Control, although a USAF evaluation suggests the need for top-level coordination of the reliability effort.

It must be remembered that reliability has always been a desired attribute of any consumer item. Cost determined how much you got of it. Reliability has always been one of the design parameters, but it was slighted badly by many designers in favor of performance. Yet prewar electronic equipment was quite simple and there was not too much of it, so no great problem was apparent. Things changed following the technological revolution associated with the recent wars. Equipments have become exceedingly complex, and in the case of airborne equipments, size and weight considerations are of paramount importance. When you add the environment of a missile to these considerations, you begin to grasp the magnitude of the revolution. Reliability is still a parameter to be optimized, but the requirements for it are much higher and the difficulty of achieving it is vastly greater. The job has changed, and so has the organization to achieve it.

Convair-Fort Worth is the second largest Convair Division, employing more than 20,000 personnel. Its background is aircraft manufacture, and it produced large numbers of B-36's for the Air Force. As you all know, the B-36 is a very large aircraft with very complex electronic fire control, communications, and bombing and navigational equipment. To keep one operating was a serious task. So when the B-58 program began, Fort Worth was aware of some of the problems it would face. Here was to be an entirely new bomber with supersonic dash capability beyond any operational air-

craft, powered by a new engine, involving new construction materials and methods, and carrying the most advanced bomber-navigation system so far conceived. Admittedly, Fort Worth would not make the bomber-navigation, or for that matter, any of the complex electronic equipment which had to be packed in the fuselage like sardines in a can. (Unlike the sardines, however, this electronic equipment generated heat to be dissipated and was capable of absorbing heat from the aircraft skin during supersonic flight.) But its systems managers had to specify and evaluate what they were procuring. Now there was no production in this case, although hopes for the future were high.

The concepts of reliability were gradually evolving throughout the Department of Defense during the early development stage of the B-58. These concepts and the resulting requirements impacted over a period of time in such a manner as to allow reliability functions to be absorbed in or assigned to existing structural elements. However, because so many parts of the organization had responsibilities for reliability, Chief Engineer Frank Davis evolved a novel and interesting structure which appears to be working satisfactorily as of now. This new engineering perspective may best be described in Davis' own words.

"The product of an engineering department is ideas. Expressed verbally, graphically, and in many other ways, these ideas are transmitted to other elements of the organization who translate them into usable hardware. The final form and character of the hardware is established by many individual design decisions. The considerations entering into each decision come from three directions:

"1. The objectives of the particular project in question; i.e., project management.

"2. The desire to achieve certain product qualities; e.g., safety, performance, reliability.

"3. The specialized engineering skills involved in design decisions; e.g., aerodynamics, thermodynamics, structural design, etc.

"The areas considered as product qualities are indicated as staff functions. Each of these qualities has a center of gravity in one of the line organization groups or sections. The assignment of the staff responsibility (to the Chief Engineer) has in each case been made as a dual assignment to the particular line supervisor who has within his line organization the necessary skill, know-how and manpower to accomplish planning, programming, advice, and follow-up required in the staff function."

Thus, Mr. Reade appears on the organization chart as a staff function for the Product Quality-Reliability. He also appears in the line under the Chief Design Engineer as Head of Systems Installation, Systems Reliability, and Malfunction Analysis.

It is quite probable that some shift will occur in the organization as the B-58 goes into production, but I do not think it will be major. It is built on what I believe to be a basically sound concept. Apropos of this, I could not have studied the problem as I did for the last years at DOD without having evolved a philosophy of management as it relates to reliability programs. I would like to quote from a presentation I made to the management group at Convair-Fort Worth and Chance Vought in November, 1956. I haven't changed my concept since that time, not because I'm too stubborn or pigheaded to change, but because all lately evaluated evidence tends to support the theory.

"Now, since reliability has been shown to apply throughout the industrial cycle, industry has had to face a novel organizational problem. Industry reaction was, in the first impact, characterized by two widely divergent directions. One direction was to emphasize, by educational processes, the over-all responsibility for reliability. Big signs carried the slogan 'Reliability is Everyone's Business' and since this was all that was done in many cases, the corollary followed that 'Everyone's Business is No One's Business.' A second direction was the establishment of a highly integrated reliability group with selected personnel from Engineering, Manufacturing, Marketing, etc. The first technique produced little, if any, real effect although certainly an educational effort is an essential part of any good reliability program. The second tended to divorce responsibility for reliability from the very individuals who, in the last analysis, were responsible. A realization has come about gradually that since the responsibilities for reliability are individual and throughout the entire industrial cycle they will be most effectively excercised when they are buttressed and serviced where they exist by a modern management function whose only area of specialization and operation is reliability.

"Once such an organizational philosophy has been decided upon and the composition and duties of the group determined, the next management task is to determine where to locate the function -- where should it be and to whom should it report? It appears that a fundamental axiom applies here; i.e., to be effective it should report high enough so as to be assured it can implement its responsibilities for reliability. Once that has been said, it is up to the individual company to determine the specific location and report structure. Some companies have a vice-president in charge of the entire reliability program; others use a committee structure in an executive position just above the Engineering, Marketing, Manufacturing, etc., Divisions; and many managers retain the responsibility themselves. Where the reliability program is located is an expedient basically dependent upon the corporate structure -- its composition and where it reports are the all important factors."

I shall go over the organizational activities of the San Diego Division very briefly. This is

the largest and oldest of the Convair divisions, employing more than 25,000 personnel. Its product line is aircraft, although it has served as a spawning ground for ideas which turned out TERRIER, ATLAS, and other projects now carried as separate divisions. A reliability program has been set up by Division Regulation with the purpose of establishing the basic policies, procedures, and responsibilities required to insure the attainment of the highest degree of reliability in the development and manufacture of Convair-San Diego products. A Reliability Policy Committee has been instituted with the following members: Assistant Chief Engineer (Chairman), Chief of Reliability, Human Factors and Acoustics, Engineering; Manager of Contracts, Factory Managers, Manager of Manufacturing Development and Process Specifications, Manager of Material, Manager of Quality Control, Chief Tool Engineers.

It should be noted that the Chairman is not the reliability coordinator. A second noteworthy item relates to the size of this organization, a factor which will make it difficult to assemble and to arrive at decisions. However, its first function is to set up policy and probably subsidiary organizations and broad representation is required. I have not observed its operations. But since the establishing decument was made effective as of September 30, 1957, I believe it to be relatively new, and later experience may modify the structure. San Diego is responsible for the development and production of the USAF F-102 - F-106 interceptors. These aircraft have very complex fire control systems. Unlike the Fort Worth B-58 program, however, where that company is Weapons Systems Manager for the entire aircraft, the responsibility for the fire control systems of the USAF F-102 - F-106 aircraft belongs to Hughes, where a very substantial reliability effort is sponsored.

Convair-Astronautics, employing about 8,000 personnel, is the newest Convair division. It is set up expressly for the development and subsequent manufacture of the ATLAS ICBM. Since it was missile-oriented in its inception, this statement of Manager J. Dempsey is not surprising:

> "Reliability is not only the function of a special reliability group which we have set up, but must be an inherent part of our basic design and manufacturing philosophy. To this end, we have in the division a Reliability Committee, chairmaned by the Division Manager, and including our senior technical and manufacturing people. The emphasis on this committee's activities is placed on integrating reliability concepts to our line management structure."

Mr. Eppenstein, Supervisor of the Reliability Group, Engineering Department, states that the effects of the reliability requirement have been much less pronounced than was expected early in the development of reliability programs. The changes which have taken place are not drastic. In most instances, the only outward evidence of the initiation of the reliability activities has been the creation of a reliability organization as a new element within the over-all company organizational structure. The Reliability Group does "bird dogging," data handling and analysis, and promotion of a return to the valuable teamwork aspect of the old guild. There have, of course, been increases in assignments to existing structures but, in the main, the impact at Astronautics is the total acceptance by all division members of the need for reliability and a realization of the disastrous consequences of unreliability. The competition, nationally and internationally, for a highly reliable missile is extremely keen.

The Pomona Division of Convair employs about 5,000 personnel. Since its inception it has been missile-oriented, although it did originate as part of the San Diego Division. This has had an interesting history in the development and production of the TERRIER missile. Now, TERRIER was originally designed as a test vehicle for the TALOS. The decision to produce TERRIER found Convair in the position of attempting to make the best of a bad situation, that is, reliable mass production of a had-made device put together with the basic idea of testing developmental concepts.

The Convair organization at that time was established primarily along typical aircraft lines. Little formal reliability effort existed then beyond a program for performing environmental tests on each of the TERRIER components to see if they could qualify under established specifications. From the outset this test program was in serious trouble due to the inability of the components to perform under the conditions which had been established. Inspection was organizationally separated from the engineering and manufacturing operations performing primarily the routine functions associated with insuring reasonable standards of workmanship. During this formative period, one K. T. Keller stepped in and added considerable pressure to get results. And in addition, the whole activity was transferred from San Diego to Pomona!

The establishment of a formal reliability group within the Engineering Department was among the first of several basic organizational changes. A joint engineering-inspection program for reporting component failures followed. This effort was in itself not particularly effective until a failure diagnosis group was added, made up of high-caliber design engineers working as a team with representatives of the Inspection and Manufacturing Departments. This diagnosis team was given the broad authority to stop factory operations until a thorough diagnosis of the underlying causes of failure were determined. The functions of Flight Test and Flight Analysis were separated, which had the effect of concentrating more effort on the analysis and correction of flight failures. Procedures were established for the reporting and feedback of all findings to groups responsible for taking corrective action.

As soon as the production and flight problems smoothed out, the formal reliability group was transferred to a newly formed Quality Control Department, also responsible for the inspection function. This quality control group, headed by

a very competent design engineer, reports directly to the General Manager. The failure diagnosis effort, under a joint engineering-inspection factory team, has been continued. The Flight Analysis Group within the Engineering Department maintains a rapid system for feedback of flight-failure information to design groups. There are, in addition, a number of special purpose committees who evaluate product design, manufacturability, and the like. The Pomona organization is characterized by the lack of any special reliability coordinator whose job it is to see that all possible techniques are being used and to monitor the outputs. However, the size of the organization permits all echelons of management to be continually aware on a day-to-day basis of any performance or reliability problems, and the General Manager does not take the responsibility lightly. In effect, the General Manager and the several Assistant General Managers become the final Reliability Policy Committee and Review Board.

An interesting comment on the factors which have generated the present high reliability of the TERRIER missile comes from one of the responsible design engineers. He states that missile development forces a contractor to place heavy emphasis on test equipment, and that frequently as much time is spent on the development of test equipment as on the missile itself, with this emphasis having its impact on the organization. I quote him as saying, "We now recognize that our success in design of test equipment is a major factor in the ultimate reliability of our missiles."

One last description. Canadair has recently been making plans to manufacture an air-to-air missile. Canadair is one of the two largest aircraft builders in Canada, employing about 9,000 people and heavily aircraft-oriented. This missile has been developed by another company, but has not been fully tested. Canadair had limited previous experience with the VELVET GLOVE air-to-air missile, which was cancelled some time ago. Contracts were slow in being awarded. (I believe we sometimes have that problem here in the United States too.) Therefore, Canadair has had ample time to plan to produce. Their planning clearly shows the effect of reliability requirements which are foreseen and evaluated early in the cycle. It also clearly shows the effects of previous history and product line.

The two main divisions of Canadair are Engineering and Production. Historically, the emphasis has been on production so most of the tools came under Production cognizance. Quality control, instead of being a division equal to Engineering and Production, falls under the latter. Thus Production, in effect, monitors itself. Engineering and Manufacturing have been divided into two branches, one for missiles and the other for aircraft. This is the first organizational shift. Experience of other missile manufacturers has been evaluated by Canadair, and they have concluded that the coordination of the various aspects of reliability requires a special organization of its own. First, this special organization must evolve a company-wide policy of reliability; secondly, it must provide regular channels by which reliability data could be collected, analyzed, and formulated into recommendations; and thirdly, it must provide means by which these recommendations can be brought to the attention of the departments concerned for corrective action.

The special organization involves the establishment of the position of Reliability Coordinator who, though he reports to the Chief Engineer (Special Weapons), would have responsibilities which would cut across departmental lines. A Reliability Policy Committee is proposed, with a Director of Quality Control, Chief Engineer (Special Weapons), and a Director of Manufacturing, as members with responsibility for reliability policy or revision of policy. Directly responsible to the Reliability Coordinator would be a Reliability Operations Committee composed of representatives from Quality Control, Engineering, Manufacturing, and Sales and Service. This group would take action on problems whose manifestation depends upon collection and data analysis. The more apparent problems would be handled by a Reliability Review Board, a special board set up to handle reliability complaints as they occur. Specific members from each department would be assembled to handle the particular complaint as a board and to take appropriate action. The Reliability Coordinator would act as Chairman of this Reliability Review Board.

All this represents a very carefully thought-out program. It has some obvious weaknesses, but they are predetermined by previous history. Programs can be carried on with inefficient organizational structures; this is happening daily. But good organization expedites the end product; it does not hamper its achievement.

From these and many other related observations, I hope I have proved my thesis: that reliability requirements do have an impact on organization; that the impact is in the direction of adding functions, redefining functions, and changing or modifying structures; and that the changes in organization depend upon the past history of the company, its product line, its size, and the time in the development cycle the reliability requirements are evaluated by management.

I would like to close my remarks with a quotation and a comment. The quotation is from the data I received from Astronautics:

> "Of interest is the fact that recognition of the reliability requirements of airborne electronic equipments has indirectly brought about a significant forward step in many other areas of industry. Specifically, it is being discovered that as the reliability programs, generated and given impetus by the reliability requirements of airborne electronic equipments, spread into fields such as hydraulics, pneumatics, structures, and electric power, startling new gains are being realized. It appears more and more likely, as experience with reliability programs is accumulated by an ever increasing number of organizations, that the broad field

of electronics -- and in particular the field of airborne electronics -- is no more fertile an area for application of reliability concepts than a host of others not previously considered ...and extending as far afield as commercial organizations who provide only services as their product."

In my estimation, we have only begun to realize the full potentialities of achieving high reliability. Too many executives give only lip service to the concept. I have noted two tendencies lately. One of these relates to the quackery and empire-building inclinations of humans to capitalize on a popular concept such as reliability. This is not applicable to the divisions of General Dynamics, where I feel our pursuit of reliability is certainly not too extensive, but it does apply to some elements in the missile industry. The second tendency is the reaction to this fraud which inevitably follows both in the company concerned and in those companies who watch the problem from the outside. Such quackery and empire building are intolerable, but when we "throw the rascals out" let's be careful not to throw out the "potatoes with the potato water."

CURRENT MILITARY RELIABILITY SPECIFICATIONS

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In general, the work engineers perform in writing, reading, interpreting, and discussing specifications is not counted among the more exciting part of their activities. In the field of reliability engineering today, however, the spotlight is very much on the subject of specifications. We are clearly on the threshold of a major breakthrough in this area. We have been talking about and experimenting with reliability specifications for a long time now; we have seen in the past an occasional application of such specifications, but in the months ahead we must be prepared for the inevitable fact that reliability specifications will be applied to every major contract assigned by the Department of Defense. This is an appropriate time, therefore, to comment on some of the feelings and attitudes of military contractors towards the whole subject of reliability specifications.

One important point should be clarified at the outset. Contractors of military equipment are not opposed to the application of reliability specifications to their products, nor do they fear that these specifications will make it more difficult for them to produce satisfactory equipment. On the contrary, the present general absence of concrete reliability specifications is presenting them with a confusion of insurmountable problems in building and testing equipment, and getting acceptance of the end item. Let us consider this situation for a moment.

For several years now, we have heard repeated requests from the Military for increased equipment reliability. It is the sincere desire of most contractors to supply equipment with both functional adequacy and the necessary reliability. Reliability, however, is not a characteristic which can be applied to the equipment like an additional coat of paint. It is a complex intangible requiring for its attainment a difficult and basic effort on the part of the contractor. In reaching for this objective, he has every right to expect that the Department of Defense, which so badly needs reliable equipment, will give him all the help possible. The most urgently needed help currently required is a workable and meaningful specification or set of specifications. Let us look at some of the problems facing the contractor who attempts to produce high reliability equipment without a set of specific requirements from his customer.

In the first place, despite the undeniably great economic value of reliability programs, these programs are initially expensive. If the contractor allows for the additional expenditures in his proposal, he runs a risk of becoming noncompetitive. If he doesn't allow for them in his proposal, he cannot justify the additional manpower required, the production of additional equipment for testing, nor any of the other expenses of a reliability program. The end product is finally delivered at a price of $100,000 instead of $115,000, and a million dollars is spent over the next five years patching it up in the field. A good reliability specification, on the other hand, would have the effect of demanding the proposal of an adequate reliability program, would lead to provision of proper funds, and would insist upon the accomplishment of the program and delivery of reliable hardware.

Another problem is that it is not always easy to convince top levels of management that it is necessary to set up an organization capable of directing the reliability effort on the various military contracts being handled by that company. A reliability organization does not spring up overnight any more than an engineering or a quality control organization can be created instantly. Once the Department of Defense defines a clear reliability policy, implemented with specifications, industry will know what will be expected and can take the necessary organizational measures.

Perhaps the most important problem of all is that contractors cannot live with meaningless contractual obligations to produce "high reliability equipment" or "equipment sufficiently reliable for its intended use." They must be relieved of playing guessing games as to what reliability means and what constitutes reliable equipment. Again, only meaningful and precise specifications can clear the air.

There is little doubt, then, that reliability specifications are needed and that their lack causes serious difficulties. The various agencies of the Department of Defense have, of course, been aware of these problems. But the mere existence of a problem does not automatically produce a solution. Considerable work had to be accomplished and, in effect, the theory and practice of reliability engineering had to be advanced before technically valid specifications could be written. Much of this work was undertaken jointly by the government and by industry, culminating in such recent reports as those of the AGREE Committee and the Ad Hoc Committee for Guided Missile Reliability. Both committees function under the direction of the Office of the Assistant Secretary of Defense; the former has been concerned with the reliability of all nonmissile electronics, while the latter has been working solely on missile reliability.

The AGREE Committee recently released a report resulting from a two-year study by nine Task Groups. The assignments of these nine Task Groups is listed below.

AGREE Report of June, 1957
(OASD/Eng.)

Task Group	
1	Numerical reliability requirements
2	Development model tests
3	Pilot production and production tests
4	Specification of design procedures
5	Specification of component parts reliability
6	Evaluation of procurement practices
7	Packing, shipment, transportation practices
8	Study of effects of storage
9	Study of services maintenance procedures

This report is being utilized by the services in the creation of reliability specifications for future electronic equipment, and as such, is highly recommended for your study. The work of the Missile Reliability Committee has progressed to the stage of issuing a first draft for industry comment. In many areas, the findings and recommendations of these two comittees are very similar.

Now that we have covered the general area of the reliability specification problem, let's take a look at some of the more specific actions which have been taken by the Military. In July, 1956, the Department of Defense issued a directive on the subject of the approval of new electronic equipment for service use. This directive, DOD 3222.1, shows a full understanding of the need to specify reliability requirements. Perhaps we may quote one or two phrases from this directive: It is required to "determine from engineering tests the ability of the equipment or system to meet the technical performance requirements." Here we have a clear indication that technical performance requirements, among which we must certainly count reliability, must be evaluated through a testing procedure.

We quote again: It is required to "determine by suitable tests the ability of the equipment or system to meet the operation performance requirements in a service or simulated service operational and maintenance environment." Again, a clear indication of the need for testing. But later on, the directive is much more specific -- pilot production is required "to provide sufficient numbers of the new equipment or systems to permit a realistic evaluation of performance and reliability," and "to permit the determination and correction of design deficiencies affecting producibility or reliability before large quantity production for service use is undertaken." Even today, it might be mentioned in passing, many electronic systems are being designed and produced by the most conscientious of contractors, many of whom cannot legally utilize any of their production for meaningful reliability tests. The Department of Defense directive ends with instructions to each military department to implement the policies and procedures which have been outlined.

We shall now discuss what the contractor would like to see contained in a reliability specification. We speak, of course, only as representatives of American Bosch Arma, but the ideas we are expressing here are endorsed by a large cross section of industry with whom we discussed these matters.

There are two types, or species, of reliability specifications which are needed -- the general and the specific. The first type sets forth a reliability philosophy applicable to a reasonably large class of equipment, such as missile electronics or shipboard radar. The second type sets forth specific reliability requirements for specific equipments or systems, such as the inertial guidance system for the Titan missile, or the tail defense system for the B-52 bomber.

MIL-R-25717B, written by and for the Air Force, is an excellent example of the general reliability specification. It deals with such matters as the degree of responsibility given to the contractor, the organization necessary for the design and production of high reliability equipment, the relationship between quality control and reliability, the necessity for failure reporting and analysis, the control of subcontractors and vendors, and other items of a similar nature. Also, while making six references to the "detailed specification for the particular equipment" for quantitative reliability requirements and the method of proving conformance thereto, MIL-R-25717B also contains suggested test methods and sample quantitative requirement statements which may be utilized. In addition, the spec makes reference to the AGREE report previously mentioned for general guidance.

MIL-R-25717B covers a large but manageable group of equipment, specified as electronic equipment. A specification of this nature aids the contractor immeasurably in forecasting what the Air Force will expect of him in fulfilling a contract for electronic equipment. He sees the necessity for setting up a reliability organization; he knows the degree of reliability responsibility he must assume; and he can deduce the effect of the reliability effort on all parts of his organization. He is not told very much, however, about the specific reliability requirements applicable to any particular piece of equipment to be produced now or in the future. For this information, he is referred to the detailed equipment specification, an approach which we feel to have merit.

BuAer Specification MIL-R-19610 is an example of the detailed specification. It is being applied only to airborne TACAN equipment. This specification has caused much discussion, both pro and con. Whatever may be ultimately right or wrong with this document, there is no question that it gives most of the information necessary to fulfill contractual reliability obligations. The contractor is given the numerical reliability requirements in a form which is meaningful in terms of the equipment covered; he is told what tests he must run, and (although indirectly) the quantities he must test. Also, we are told that the equipment produced to this spec was of much higher re-

liability than that which was produced without a reliability spec.

We would not wish to hold up either of the documents we have discussed as perfect examples of reliability specifications. It may well be several years before we can approach a state of perfection in this area. It is clear, however, that both of them represent enormous advances over anything seen before and provide at least a basis upon which work can be continued.

We will conclude by listing below the requirements which we believe should be contained in and form the central core of the set of specifications, both general and specific, leading to the design and production of high reliability equipment. These specification needs are:

1. Reliability organization
2. Reliability plan
3. Numerical reliability requirement
4. Component parts
5. Subcontractor reliability control
6. Reliability check points
7. Failure reporting
8. Reliability improvement program

The specifications should outline the form or alternate forms of reliability organization which a contractor should have available to fulfill his obligations in this area. This is certainly as necessary as the contracting agency's requirements for a proper quality control organization, a proper purchasing organization, and evidence of an engineering organization capable of performing the required tasks.

The specifications should call for a contractor to submit a reliability plan with the initial proposal, and to follow this plan with implementation details early in the development phase of the contract. It is our opinion that a specification should not describe minute details of reliability work, but should rather require that the contractor submit sufficient information for customer evaluation and approval.

A desired numerical reliability must be stated in terms which are meaningful for the specific equipment designed. In other words, careful consideration should be given to expressing the desired reliability in terms of mean-time-to-failure, probability of success, or permitted failures in a given time period. Moreover, this requirement must be clearly defined. If it is stated that no failures must occur in a given test, both the meaning of "test" and the meaning of "failure" must be given clearly.

It must be recognized that system reliability is dependent on component part reliability and must clearly state what is expected in the area of component parts. While the burden of reliability must be placed on the prime contractor, the parts vendors must be brought into the picture, and the reliability specification must allow for such inclusion. We will never have reliable equipment if the thousands of component part vendors with whom we do business are not made to appreciate fully the problems we face. At Arma we have found vendors desirous of bettering their products and of meeting our specifications. However, in order to accomplish this goal, we had to make them part of the team, with a thorough knowledge of our goals and parts problems. Test data is being supplied to vendors and parts are being improved as a result.

The specifications must place upon the prime contractor the necessity for subcontractor reliability control, but he must also receive military support and contractual coverage for such control. They must allow for the evaluation of reliability and for certain check points in the program for the assessment of reliability. When reliability tests are called for, the contract must clearly assign systems, assemblies, and/or parts for that purpose.

A suitable failure reporting program, specifying its use for over-all reliability control, should be described. Failure reporting should continue well into service use of the equipment, and proper allowances must be made for this long-term effort. When we say failure reporting, we include the associated tasks of operating time recording and suitable equipment logs.

Finally, the specifications must allow for the fact that even with the best of techniques and the best of intentions, the equipment can never be designed for its ultimate reliability potential. As experience is gained in the use of the equipment by the customer, a need for improved reliability in certain areas usually becomes evident. Consequently, allowances must be made for a reliability improvement program.

We have given our comments on the present status of reliability specifications and what we believe should be the aim and function of these specifications. We believe that our opinions are shared by the majority of military contractors. In any event, there can be little question that large-scale application of reliability specifications is coming soon. With them, and as a consequence of them, will also come a step increase in the reliability of the equipment we produce.

RELIABLLITY TECHNIQUES FOR ELECTRONIC CIRCUIT DESIGN

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A new approach to the problem of designing reliability into an electronic circuit is the method of synthetic sampling. This method is superior to the commonly used "worst-case" design philosophy, which is characterized by the requirement that the circuit operate reliably when the components are at specified adverse limits.[1] We shall point up this superiority by considering several shortcomings of the worst-case philosophy, as follows:

1. It makes no distinction between the probability of mean and extreme outputs. In view of the nature of the output distribution, this is often unrealistic, unduly pessimistic, and costly.

2. If a circuit can fail in more than one way (for example, from too high an output and too low an output) no distinction is made between the probabilities of failure from the different causes. This unbalance in reliabilities, as an example will show, may actually make it desirable to design failures from one cause into a circuit purposely, in order to increase the over-all reliability.

3. It provides no measure of reliability. The specification of limit component values for the worst case is somewhat arbitrary, and the designer never knows how much reliability he has bought by using one or another set of extreme component values.

Synthetic sampling does not have these weaknesses. It automatically weighs each output with its probability, and it gives the reliability of the circuit based on the actual component distributions. The method is illustrated in this report by application to a typical transistor switching circuit.

Improbability of Extreme Cases

Design engineers have questioned the worst-case criterion on the ground that the occurrence of the worst case may be quite improbable, and the requirement that the circuit operate under these conditions may be too costly for the reliability that it buys. Statisticians may recognize the central limit theorem in this phenomenon.[2] Our first object is to formulate a measure of it -- some rule of thumb to back up the engineer's intuition.

Suppose we have a circuit whose performance parameter y is a function of several circuit parameters,

$$y = f(x_1, \ldots, x_n).$$

We assume the design engineer knows the distribution of each component. This information may be in terms of the distribution of the deviation of the component from its nominal value.

The deviation of the performance parameter is given approximately by the total differential formula,

$$dy = \frac{\partial f}{\partial x_1} dx_1 + \ldots + \frac{\partial f}{\partial x_n} dx_n. \tag{1}$$

Using the fact that the distribution p_i of

$$dy_i = \frac{\partial f}{\partial x_i} dx_i \tag{2}$$

is related to the distribution f_i of dx_i by

$$p_i(dy_i) = \frac{1}{\frac{\partial f}{\partial x_i}} f_i\left(\frac{dx_i}{\frac{\partial f}{\partial x_i}}\right) \tag{3}$$

the problem of estimating the likelihood of some deviation becomes the problem of estimating the sum of several random variables,

$$dy = dy_1 + \ldots + dy_n. \tag{4}$$

This can be done by means of the composition of distributions formula of statistics:

$$p(z) = \int_{-\infty}^{+\infty} f(x)g(z - x)\, dx \tag{5}$$

where $z = x + y$, f is the distribution of x, and g is the distribution of y.

Figure 1 illustrates the distribution of the um of two random variables, each uniformly dis-

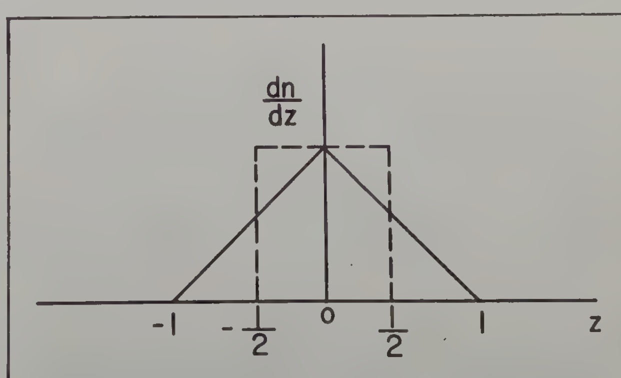

Fig. 1 - Distribution of $z = x + y$.

tributed from $-\frac{1}{2}$ to $+\frac{1}{2}$, as found by the above formula. The result agrees with intuition — the probability of the sum being near -1 or +1 is less than the probability of the sum being near 0.

If we now let f be the distribution we have just found for the sum of two variables, and reapply this formula, we get the distribution of a sum of three variables, and so on, to n variables (see Appendix). The result of all this is the following: If the deviation of an output can be considered as a sum of n uniformly distributed and approximately equal random variables, then the probability of a deviation falling within an extreme nth of the total variation is roughly $1/n!$. It is clear that this probability decreases as the number of components increases.

Unbalanced Reliabilities

We now consider a second blind spot of the worst-case design philosophy. If the circuit has more than one output, there is no indication of a possible unbalance of the reliabilities with respect to each output. A circuit may be designed to operate when any particular combination of its elements are at the limits of their initial tolerances or end-of-life tolerances, but this does not insure that its mean output will be maximally distant from all regions of malfunction.

Related to this is the fact that the nominal value of an output (obtained by inserting the nominal values of the components in the circuit equations) is not the same as the mean value of the output, intuition notwithstanding. On the contrary, if $y = f(x_1, \ldots, x_n)$ and x_i are independent, the relation between nominal value and mean value is given by a Taylor series whose first terms are:[4]

$$\bar{y} = f(\bar{x}_1, \ldots, \bar{x}_n) + \frac{1}{2} \sum_{k,\,l=1}^{n} \sigma_l \sigma_k \left. \frac{\partial^2 f}{\partial x_l \partial x_k} \right|_{x = \bar{x}} + \ldots \qquad (6)$$

Note that if the function is linear, mean and nominal values are the same.

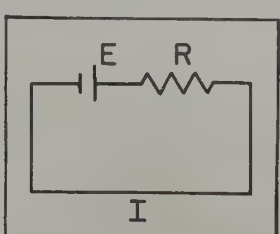

Fig. 2 - Simple series circuit.

The discrepancy between nominal and mean values is not merely of theoretical interest, confined to unusual circuits rarely encountered in practice. A close examination of the simple series circuit in Fig. 2 illustrates this difference.

Let E = 1 volt and R = 1 ohm, and suppose that R is uniformly distributed from 1/2 to 3/2. In this case the nominal value of I is 1, but the

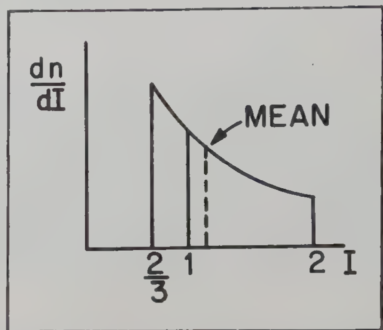

Fig. 3 - Unbalance of reliabilities.

mean value is log 3. The probability density function is $1/I^2$, as shown in Fig. 3. Thus the probability of a failure because of too small a current is greater than the probability of failure from excess current. If a design engineer knew of this unbalance, he could compensate for it by choosing R less than 1.

Measure of Reliability

A third difficulty with the worst-case design philosophy is that it provides no clear measure of reliability. An engineer using this method will have the satisfaction of knowing he has considered reliability, but he will have no measure of the effectiveness of this consideration. This is really the key question of the entire reliability problem. To answer it we need the output distribution. This in turn not only gives a measure of reliability, but also tells us how the output is distributed between its extremes.

There are several methods in the literature for estimating the distribution of the output of a circuit. A rather popular one equates the mean to the nominal value, and estimates the standard deviation of the performance parameter y from

$$\sigma^2(y) = \sum_{i=1}^{n} \left[\frac{\partial f}{\partial x_i} \sigma(x_i) \right]^2 . \qquad (7)$$

Then, assuming a normal output, its probability density is given by

$$p(y) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp - \frac{(y - \bar{y})^2}{2\sigma^2} . \qquad (8)$$

This has been called the "propagation of error technique," because of the application of Eq. (7) to computation of precision measures.[5]

A second method, also using the linearity assumption, is based on the composition of distributions formula, as shown in Eq. (5). This has the

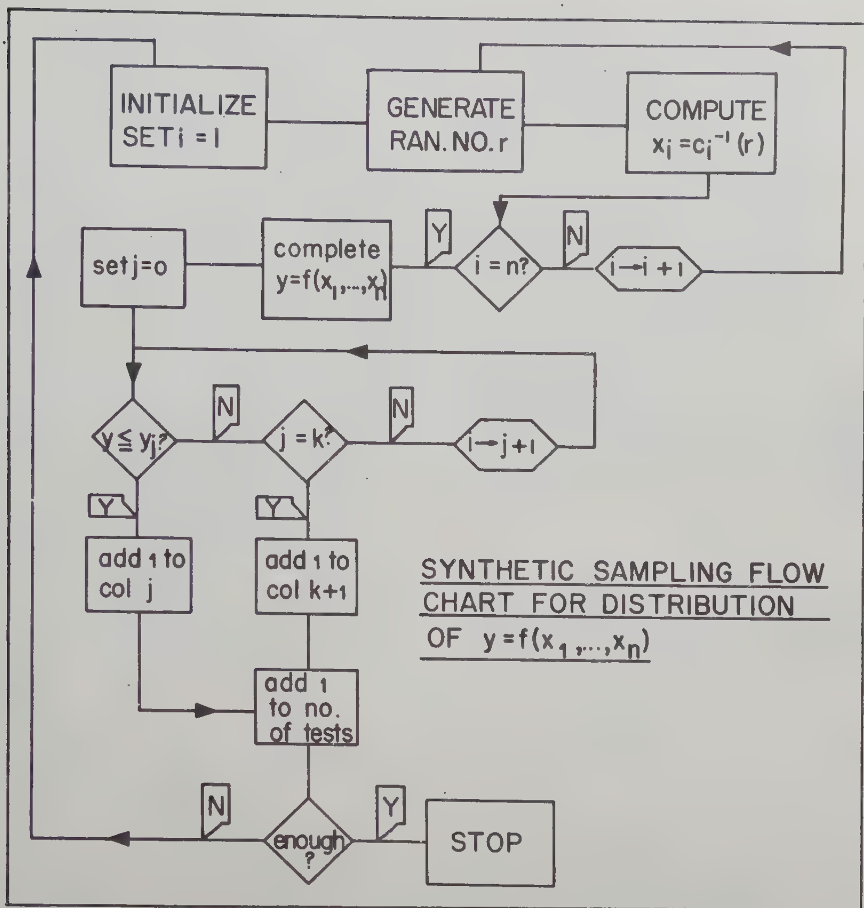

Fig. 4 - Flow chart for the synthetic sampling method.

advantage over the propagation of error technique because we are not restricted to normal distributions. In the study of the extremes of the distribution function, the normal curve would have been quite unsuitable. Its tails, trailing off to $\pm\infty$, would have submerged the very thing we wished to observe.

The Method of Synthetic Sampling

The method that we have found best for ease of application, adaptability to available component data, and accuracy is Monte Carlo.[7] In general, the essence of Monte Carlo methods is the conversion of a problem to some equivalent statistical one and then solving this experimentally by observing a large number of cases. A classical example is integration.[8] Our problem is a natural one for Monte Carlo, for it is essentially statistical to begin with and needs no conversion. For this reason it has been called synthetic sampling.

Suppose we wish to obtain the output distribution of

$$y = f(x_1, \dots, x_n)$$

where the x_i are distributed in a known way from a minimum of x_{ia} to a maximum of x_{iz}. We assume that the cumulative distribution function c_i of the ith component is such that, corresponding to any random number between 0 and 1, there is a unique value of the parameter.

The flow chart for the synthetic sampling method is shown in Fig. 4. The y_j's are a set of test points for the distribution. When the testing is over, column 0 will contain all the cases less than y_0, column 1 will contain the number of cases between y_0 and y_1, and so on. Note that the y_i need not be equally spaced, but can be chosen to highlight any particular region of the distribution.

You may ask, what faith can we have in answers obtained in this way -- by chance, so to speak. How do we know that we can trust the random number generator to be unbiased? The answer is that there are statistical tests that can be and have been applied to these questions and that tell us with what confidence we may believe the results. Studies of this sort should be part of a proper application of the synthetic sampling method.

However, if possible, it is always comforting to test the method on a problem for which we know the answer. For example, using the composition of distributions formula, we have computed the dis-

TEST POINTS y_i	0	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
THEORETICAL CASES	1	15	61	115	115	61	15	1	
EXPERIMENTAL CASES	.96	15.73	60.8	114.9	113.71	60.81	16.03	1.02	

Fig. 5 - Distribution of $z = x_1 + x_2 + x_3 + x_4$. Comparison of theoretical distribution for 384 cases with synthetic sampling of 38,400 cases.

tribution of the sum of four variables, each uniformly distributed from 0 to 1. This gave the theoretical probabilities for z falling into each interval of length $\frac{1}{2}$ from 0 to 4. The distribution was then found experimentally. A comparison is shown in Fig. 5.

Example

The method of synthetic sampling has been applied to the analysis of the switching circuit shown in Fig. 6. This circuit was originally designed using the worst-case philosophy, in which the transistor parameters were taken to end of life, and the other circuit parameters were at initial purchase tolerances. In our testing we let all parameter distributions c_i be uniform with end-of-life limits. Note that any other available component data could have been used as well.

Two performance parameters were considered: (1) the voltage difference $V_e - V_1$, when the cir-

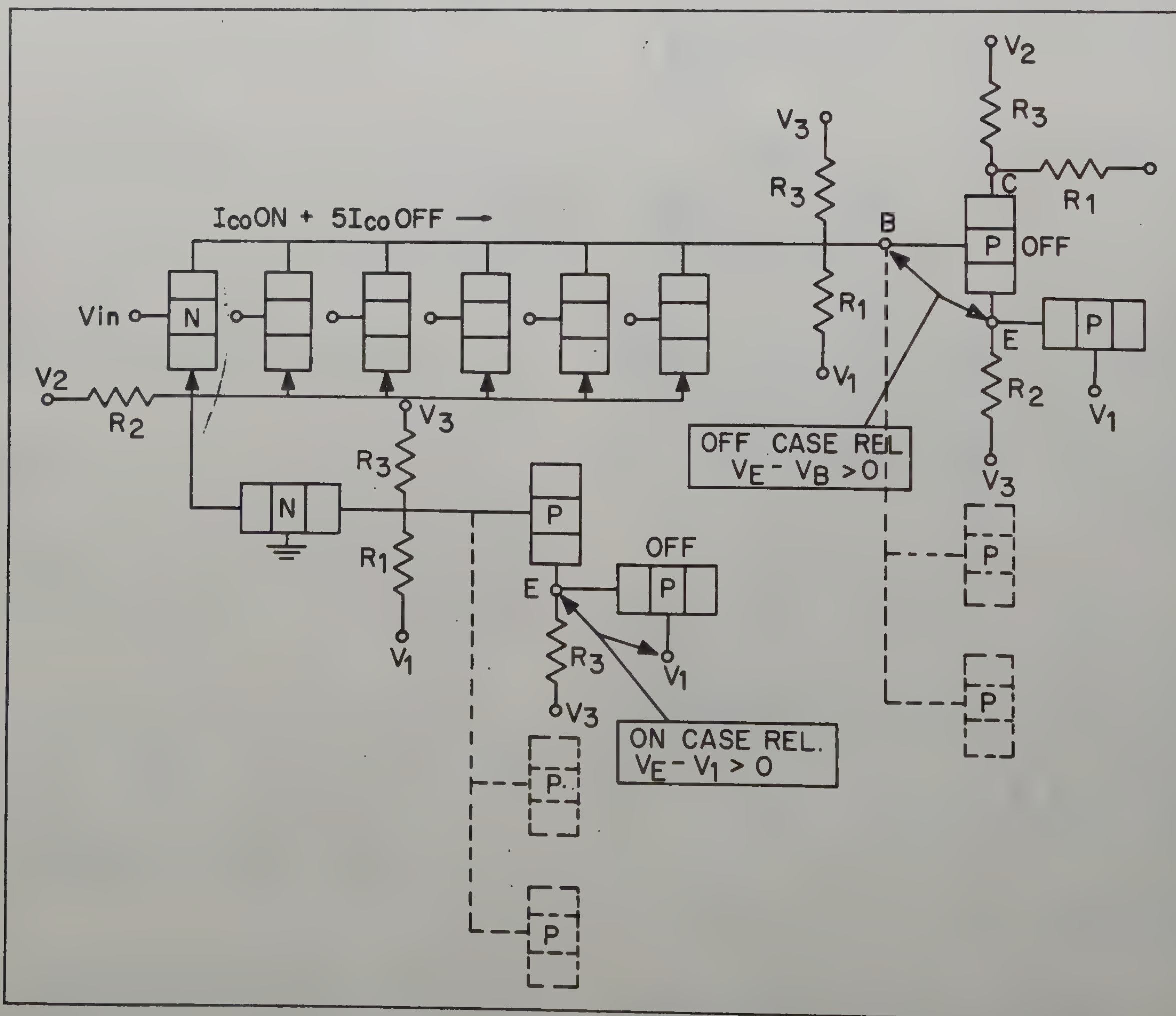

Fig. 6 - Transistor switching circuit.

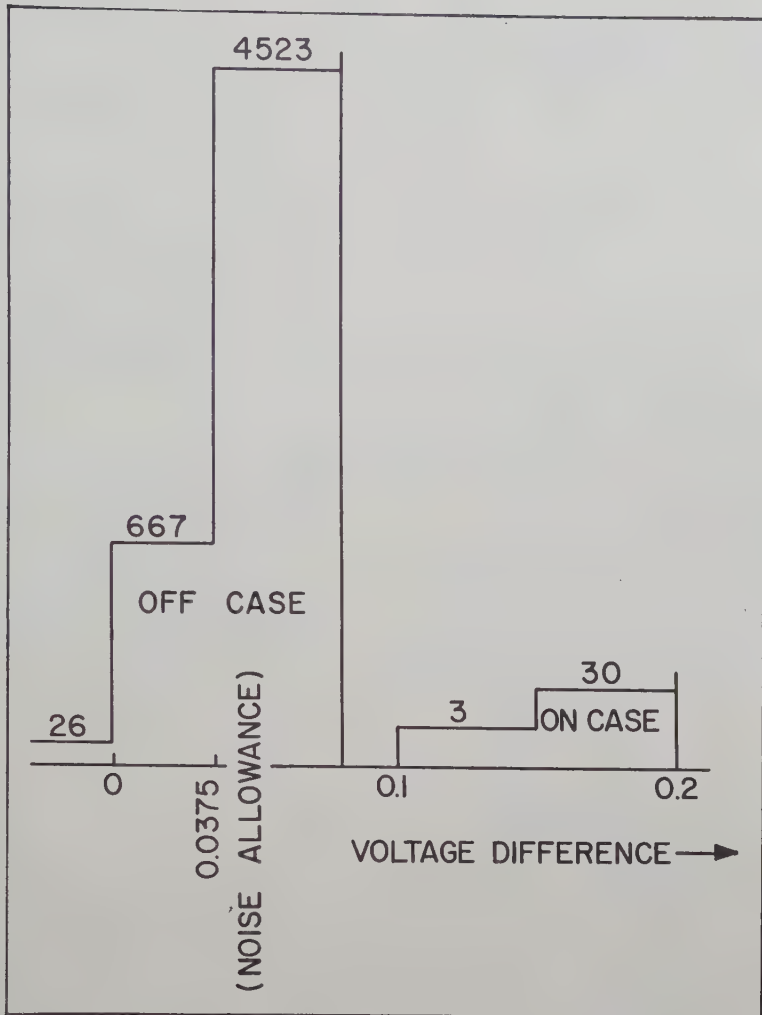

Fig. 7 - Synthetic sampling, the result of 100,000 cases.

cuit is on; and (2) $V_e - V_b$, when the circuit is off. For reliable operation these had to be greater than zero with some noise allowance.

Since we were particularly interested in the nature of the distribution in the neighborhood of zero -- for this is where failures will occur -- we chose our test points accordingly. The results of 100,000 tests are shown in Fig. 7. Note the unbalance between the on and off cases. When on, no case came near failing; when off, 693 cases were below the allowed noise level. This was a result which could not have been forseen by simply considering worst cases.

In an effort to equalize the on and off cases the resistance R_3 was decreased from its original design value of 2.7 k. As R_3 decreased, the on case became slightly less reliable, while the off case reliability improved. The optimum value appears to be between 2.3 k and 2.4 k, as shown in Fig. 8. With this value, and with the parameter distributions we have assumed, the probability of failure from parameter drift is 1 in 10,000. That is, the reliability is 0.9999.

Conclusion

To summarize, the worst-case design philosophy says: "Let the circuit operate when the circuit parameters have their extreme adverse values." In view of the shortcomings of this approach already discussed, we propose that it be replaced with the design philosophy which says, "Let the circuit operate with probability R when the parameters have their probable values." Synthetic sampling seems to be an excellent way to implement this philosophy.

Appendix

Let us denote the sum of n statistically independent variables (each uniformly distributed from $-\frac{1}{2}$ to $+\frac{1}{2}$) by x_n, and the distribution of x_n by f_n. The composition of distributions formula, Eq. (5), then gives

$$f_2(x_2) = \int_{-\infty}^{\infty} f_1(x)\, g(x_2 - x)\, dx \qquad (9)$$

where $f_1 = g$, and $x_1 = x$. With the distributions

we have chosen, the independent variables x and $x_2 - x$ are less than $\frac{1}{2}$ in absolute value. Thus

We are interested in the nature of f_n in the neighborhood of its negative extremity, $-n/2$. Clearly, from Eq. (9),

$$f_2(x_2) = \int_{\max\left\{x_2 - \frac{1}{2}, -\frac{1}{2}\right\}}^{\min\left\{x_2 + \frac{1}{2}, \frac{1}{2}\right\}} dx$$

and considerations of cases gives

$$f_2(x_2) = \begin{cases} x_2 + 1 & -1 \leq x_2 \leq 0 \\ -x_2 + 1 & 0 \leq x_2 \leq 1 \end{cases}$$

$$f_2(x_2) = \int_{-\frac{1}{2}}^{x_2 + \frac{1}{2}} dx \qquad -1 \leq x_2 \leq 0$$

Suppose

$$f_n - 1(x_n - 1) = \int_{\frac{2-n}{2}}^{x_{n-1} + \frac{1}{2}} \int_{\frac{3-n}{2}}^{x_{n-2} + \frac{1}{2}} \cdots \int_{-1}^{x_3 + \frac{1}{2}} \int_{-\frac{1}{2}}^{x_2 + \frac{1}{2}} dx\, dx_2 \ldots dx_{n-1}$$

for $\quad \frac{1-n}{2} \leq x_{n-1} \leq \frac{3-n}{2}$

Then, by Eq. (5),

$$f_n(x_n) = \int_{-\infty}^{\infty} f_{n-1}(x)\, g(x_n - x)\, dx$$

where f_{n-1} and g are zero outside the ranges

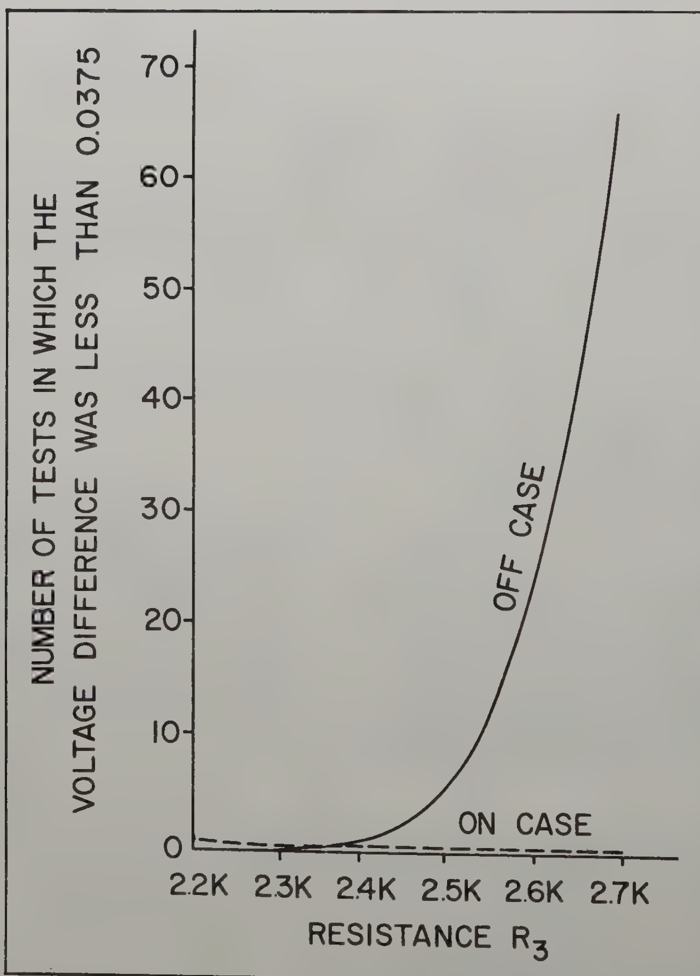

Fig. 8 - Failures vs. resistance R_3 in 10,000 cases.

$$x_n - \tfrac{1}{2} \leq x \leq x_n + \tfrac{1}{2}$$

and

$$\frac{1-n}{2} \leq x \leq \frac{3-n}{2}$$

Hence,

$$f_n(x_n) = \int_{\max\left\{\frac{1-n}{2},\ x_n - \frac{1}{2}\right\}}^{\min\left\{x_n + \frac{1}{2},\ \frac{3-n}{2}\right\}} f_{n-1}(x) \quad dx$$

For $-\frac{n}{2} \leq x_n \leq -\frac{n}{2} + 1$, this gives

$$f_n(x_n) = \int_{\frac{1-n}{2}}^{x_n + \frac{1}{2}} \int_{\frac{2-n}{2}}^{x_{n-1} + \frac{1}{2}} \cdots \int_{-1}^{x_3 + \frac{1}{2}}$$

$$\int_{-\frac{1}{2}}^{x_2 + \frac{1}{2}} dx\, dx_2 \ldots dx_n$$

for $-\frac{n}{2} \leq x_n \leq \frac{2-n}{2}$.

Differentiation of this gives

$$f_n'(x_n) = f_{n-1}(x_{n-1} + \tfrac{1}{2})$$

and for the (n-2)th derivative we have

$$f_n^{(n-2)}(x) = f_{n-1}^{(n-3)}(x + \tfrac{1}{2}) = \ldots$$

$$= f_3^{(1)}(x + \frac{n-3}{2}) = f_2(x + \frac{n-2}{2}).$$

Since $f_2(-1) = 0$, it follows that $f_n^{(n-2)}(-n/2) = 0$, and similarly for the lower order derivatives at $-n/2$. Also since

$$f_n^{(n-1)}(x) = f_2'(x + \frac{n-1}{2}) = 1 \quad \text{at } x = -\frac{n}{2}$$

we may infer that the order of contact of $f_n(x)$ at the point $-n/2$, with the x-axis, is n-2. Furthermore, since f_n is a polynomial of degree n-1, the nth order and higher derivatives are all zero. All this says,

$$f_n(x) = \frac{(x + \frac{n}{2})^{n-1}}{(n-1)!} \quad \text{for } -\frac{n}{2} \leq x \leq \frac{2-n}{2},$$

and the probability of falling in this region is

$$\frac{1}{(n-1)!} \int_{-\frac{n}{2}}^{\frac{2-n}{2}} (x + \frac{n}{2})^{n-1} \quad dx = \frac{1}{n!}$$

which is the result we wished to prove.

Alternative methods of arriving at the same result are given by Silberstein[13] and Parker[12]. The article by Berz[11] is also of interest here.

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AIR FORCE ELECTRONIC RELIABILITY PROGRAM*

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As AGREE's Task Group No. 1 has pointed out,[1] in the past a manufacturer engaged in the development of a new piece of electronic equipment was confronted with the necessity of meeting certain performance requirements. Theoretically, he was equally responsible for assuring a high level of reliability in his equipment. However, the performance requirements were stated in the specification or in the engineering exhibit in definite and quantitative terms. Thus, the manufacturer had a legal obligation to meet them. In contrast, the reliability requirements were not stated in such positive terms. Consequently, reliability was often relegated to a secondary role and, if considered at all, it was considered only after the equipment design attained the "listed" performance requirements. Experience has shown rather pointedly that reliability is not necessarily inherent in any given equipment design, that it cannot be left to chance, but that it must be considered as a specific performance requirement. It must be included in component selection and application, and it must be a part of circuit design and of the basic equipment development. This is especially true of the very complex equipments such as SAGE‡.

Several years ago the Air Force became quite aware of the fact that its electronic equipment reliability was far from adequate to safeguard the investment being made in the air vehicles in which such equipment was being installed. And with the advent of missiles and unmanned aircraft electronic equipment reliability has become more important than ever before.

Supersonic flight and the requirement for automatic weapon systems of greater and greater capability aggravate the whole problem of equipment unreliability by:

(1) Increasing the severity of the environmental conditions in which the equipment is expected to work, and

(2) The greater reliance being placed on electronic equipment.

The more severe environmental conditions result in a decrease of performance and reliability of the equipment. The greater dependence upon it results in the increase in complexity, size, and weight. In order to meet the requirements which the new air systems impose, the Air Force realized that any program of equipment development had to be backed up, not only by a sound and logical program of component part development, but also by a program of component packaging and assembly, heat transfer, weight and size reduction, increase in circuit performance, and in general in the improvement in the reliability of equipment operation. In order to give the reliability requirement sufficient weight and priority, the Air Research and Development Command (ARDC) issued in mid-1956 Technical Requirement No. 206 entitled, "Electronic Design Techniques." Its goal is to attain, by means of specific development effort, equipment design which will provide maximum overall performance and reliability per minimum of weight. This development directive required the ARDC development centers to establish specific projects which would advance the technology of electronic equipment reliability. This was to be accomplished by the advancement of techniques that would lead to:

(1) Simplification of equipment design which would take full advantage of packaging and assembly, shielding, cooling, improved form factors, heat dissipation and/or absorption, and component derating

(2) Derivation of design and trade-off curves which would represent the relationship between performance, reliability, complexity, form factors and other features of the equipment, the design data to be developed and presented in such a form that an engineer can favor the factors pointed up by the operational requirement stated for the equipment he is developing

(3) The calculation of performance, reliability, weight, size and ruggedness of the equipment before it is built, and the verification by simple tests of the correctness of the calculations after construction of the equipment

(4) Circuitry which would provide maintenance free equipment for at least 1,000 hours of continuous operation

(5) Automatic fault location and marginal checking devices for incorporation into the equipment to indicate impending failures and for the rapid isolation of failures should they occur

(6) Circuitry to avoid complete equipment failure in case of failure of one component part

(7) Establishment of correlation between laboratory and production type tests

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* Based on a presentation delivered at the Fourth National Symposium on Reliability and Quality Control in Electronics, January 6-8, 1958, Washington, D. C.

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‡ Semi-Automatic Ground Environment.

and expectancy of operational reliability

(8) Development of abbreviated quality control tests.

As a result of this directive, projects were established at the ARDC centers to develop more rugged components, more reliable circuitry, and improved quality control procedures. Mathematical studies have been started which, using the theories of probability and statistics, should result in a sound and comprehensive procedure of reliability analysis and synthesis. In other words a technique is required which, given the reliability and tolerance distribution of the components, would guide the designer in achieving the quantitative reliability expected of the specified item of equipment. This technique should also enable engineers to evaluate partial or completed equipment designs and to determine rapidly whether the equipment will meet the operational reliability figures quoted in the specifications.

Comparisons are being made (and this work is just beginning) between actual field reliability figures and theoretical and empirical predictions based on theories in development. Modifications of the prediction techniques will continue to be made until their results correlate closely with field reliability data. Several methods of predicting reliability are being tried, such as complete and detailed system's analysis, part count and use of environmental stress curves, and sampling. Test procedures are also being developed to verify whether the specified reliability figures so obtained have been met in the equipment design.

Work is under way to determine representative quantitative reliability figures for several classes of Air Force equipments which could be used in development exhibits and production specifications. This work should also aid in determining reliability requirements which could be included in component parts specifications, the problem that Mr. Child pointed up in his paper[2]. Some of the representative Air Force equipments on which studies are being conducted to determine the mean-time-to-failure are the following:

(1) AN/GRC-27, UHF ground communication set

(2) AN/FPS-3, ground early warning radar

(3) AN/UPX-6, ground identification transmitter-receiver for the Mk X System

(4) AN/MSQ-1, tactical control radar

(5) AN/ARC-34, airborne UHF communication set.

The preliminary analysis conducted on the GRC-27, minus the guard channel and under a typical 4:1 receive-transmit operating ratio, indicates a mean-time-to-failure of 399 hours. The mean life of the FPS-3 is 74 hours and that of the MSQ-1 about 30 hours.

The obstacles to overcome in completing this work are rather imposing. For example, it is difficult to determine the quantitative figures, if any, that should be assigned to such intangible effects as operator skill, maintenance level, environmental conditions, and so on.

Any reliability improvement program to be effective requires a good feedback procedure; otherwise it would be impossible to compare the theoretical reliability predictions with actual field reliability results. AF T.O. 00-20-2, "Malfunction Data Recording for Armament and Electronics Equipment" published 20 May 1957 provides a directive for acquiring and recording electronic equipment behavior and malfunction data. The purpose of this directive is to obtain information on airborne armament and electronics equipment in order to institute corrective action, but it should also serve to provide a failure reporting procedure. The current field failure reporting system in the Air Force has not proved too satisfactory for the following reasons:

(1) Not all failures are reported

(2) There is no indication as to the total number of equipments covered by the reporting system

(3) Equipment running time is often not recorded

(4) Data is not processed fast enough.

Definite measures are being taken to improve this system. One of them is the development of a running time meter called the chronister. It consists of a fuse like device containing copper sulphide, a fuse holder and a current limiting resistor. The fuse like device and resistor, connected in series, are placed in the equipment so that a current of one milliampere flows thru them when the equipment is operating. The amount of copper deposited at one of the electrodes can be read in terms of equipment running time up to 1,000 hours. In addition other ways and means are being considered to have the data recorded more accurately and processed more promptly.

Perhaps one of the major concentrated efforts in improving the reliability of any single system so far has been the work on SAGE, the Semi-Automatic Ground Environment of the Air Defense System. It was realized early in the development stage that the keystone to successful operation of SAGE lay in the reliability of component parts and circuits. This was in particular true of the central digital computer, AN/FSQ-7, as it has:

(1) Over 50,000 tubes of about 25 different types

(2) Over 170,000 diodes

(3) 547,000 resistors

(4) 189,000 capacitors.

Reliability of the computer has been improved by a number of measures some of which are the following:

(1) Duplex operation of the basic computer elements and the employment of operational spares in the case of simplex equipments

(2) Development of superior component parts such as the ultra-reliable electron tubes having a life span of 100,000 hours

(3) Application of components through circuit designs that extend component life to the maximum

(4) Marginal checking techniques, in this case a built-in capability, for the purpose of predicting and weeding out components which with time develop a high failure probability. Also the formulation and preparation of test programs which exercise the machine in rigorous electrical patterns in an effort to precipate or predict potential component failures

(5) Unit test equipment together with facilities for loop-tests

(6) Built-in alarms to isolate failures

(7) Packaging techniques that facilitate maintenance

(8) Provision of the proper operating environment for components from the standpoint of temperature and humidity

(9) Circuit designs which minimize the effects of component aging.

Reliability improvement of SAGE continues. This consists of pinpointing and replacing troublesome components and improving marginal checking and marginal test equipment. Studies are being conducted to prescribe meaningful margins to detect insipient component failures.

What has just been described could be considered as the first phase of the Air Force electronic reliability program, or that phase which leads to the advancement of the state-of-the-art. The second phase, concurrent with the first, is pointed toward increasing equipment reliability as this equipment undergoes development. Its objective is the inclusion of a definite reliability requirement in all equipment production specifications.

Several years ago the Air Force concluded that the only way basic equipment reliability could be improved was to include reliability as one of the factors that had to be met in the initial equipment design. As a result, this requirement was stated in ARDC Regulation No. 80-21 published on May 16, 1956* as a directive to be followed by all ARDC centers. This regulation states that reliability must be considered as one of the major requirements of engineering design in all phases of research and development of electronic equipment. It also states that all specifications, exhibits, product descriptions or other technical requirement documents will include as one of the major engineering factors specific requirements covering reliability. These requirements must be stated in quantitative terms consistent with the state-of-the-art and in consideration of the other design factors such as maintainability, cost, versatility, procurability, standardization, performance, etc. It also specifies that deviation from specified quantitative reliability requirements will be granted only after it has been determined that trade-off values justify such action in order to gain the desired degree of performance in some other area of consideration or to obtain a balanced overall end result. It specifies that one of the major factors in the evaluation of any contractual proposal will be a review, from an engineering standpoint, of the adequacy of the reliability program that the prospective contractor proposes to follow. Such an evaluation will include the following:

(1) Inspection and quality control methods

(2) Functional and environmental test procedures

(3) Analysis procedures and methods used to predict and measure reliability.

During the course of an equipment development contract, separate progress reports, or a separate chapter in each progress report submitted, will be required which will state clearly and concisely the contractor's efforts to achieve reliability and will show his accomplishments. The final report will show:

(1) The predicted reliability of the equipment

(2) Features of the equipment design considered weakest from the standpoint of reliability

(3) Measures taken to increase reliability

(4) Improvement attained by measures taken

(5) Conditions which might decrease reliability.

Shortly after this regulation was published, the development centers put out their own instructions enforcing this policy. Since then a number of general specifications have been written to cover a specific class of equipment. For instance:

(1) WADC's Exhibit No. WCLN-1308 of 16 April 1956 whose purpose is the estab-

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* Preliminary instructions were issued several months before this date.

lishment by the contractor, during the development stage, of a comprehensive reliability program covering airborne communication, navigation and identification (CN&I) equipment

(2) WADC's Exhibit No. WCLR-453, dated 16 October 56, which covers the procedures and criteria required to assure an adequate program for obtaining reliability of airborne reconnaissance equipment during the final development stage and prior to the production program.

These exhibits require the contractor to establish a definite reliability program. Since it is not often possible to prove statistically that a specified reliability level has been achieved, it is necessary to judge results from the proper application of certain criteria and procedures. Therefore, within 90 days after the date of the contract, the contractor is required to submit his proposed reliability program for approval. This includes the circuit design and the computations on the statistical estimate of the probability that the equipment will operate for a stated number of hours without failure or fault. Trade-off values between the performance of the equipment and its associated design characteristics (frequency, range, power, accuracy, etc.) must be balanced against reliability. In addition trade-off values must be considered from the standpoint of maintainability, cost, versatility, procurability, standardization, time scheduling, etc.

Other more general type of specifications such as RADC's MIL-E-4158, "Requirements for Ground Electronic Equipment", are being changed to include reliability requirements. Standard paragraphs are also being prepared for inclusion in equipment specifications.

Engineering groups have been appointed for the purpose of reviewing and making recommendations for improving the reliability program of the particular agency they represent. One such a group is the Intercommand Communications-Electronics Reliability Committee; another, but on a lower level has been established in the Weapons Guidance Laboratory of Wright Air Development Center.

With one exception which is being checked, all Air Force electronic equipment exhibits which have been written during the past year have included a reliability requirement. These are much more specific than the general type of specifications and spell out in detail the service life and reliability of the particular equipment and how to test for these factors. In case of lack of any other instructions, MIL-R-25717[3] is being used to establish the minimum reliability program. Some of the equipment specifications which now include reliability requirements are:

(1) WADC's Exhibit WCLN-1314 for AN/ARN-52(XA-1) dated 4 May 56 which includes a requirement that the equipment have a reliable statistical average operating life of 200 hours without the replacement of any components or readjustment of the equipment

(2) MIL-R-6471A(USAF) specification for AN/ARC-21 dated 9 October 56. This also requires the equipment to average 200 hours of operation between failures, without servicing; replacement of electron tubes is considered a failure.

Although the recent AGREE task group reports have been of great help, one of the big problems that still remains to be solved is the determination of quantitative reliability figures for the many Air Force equipments being procured, and the development of testing techniques and/or test equipment to determine if these figures have been met.

The third phase of the Air Force program covers the improvement of the quality of replacement parts. Since electron tube failures cause the greatest number of equipment failures, both the Air Materiel Command and ARDC have issued regulations which require, in the development and production of Air Force equipment, the use of the best quality and most rugged electron tubes available. ARDC Regulation No. 80-24 entitled, "Use of High Quality Electron Tubes in the Development of New Equipment", states that under no condition will an older type of tube be used if an improved tube type is available. This policy is now in the process of expansion to the operating commands. A draft Air Force regulation is in the process of coordination. It will require all Air Force agencies to use the highest quality tubes not only in development and production but also in the maintenance of Air Force equipment. It is the Air Force plan to expand this policy so that it will cover other component parts.

It is the Air Force feeling that any advances made in reliability will be of limited value unless they are put into practice. Therefore the Air Force directives also require the dissemination of the design data to electronic equipment developers to make them aware of the advantages that the new design techniques offer. As a result several general references on electronic equipment reliability or related to it have been published. Some of them are:

(1) "Reliability Factors for Ground Electronic Equipment" published first as a report in 1955, then as a book by McGraw-Hill Book Company[4]. However, in the last two years the reliability field has progressed so fast that the handbook already requires revision.

(2) "Techniques for Application of Electron Tubes in Military Equipment", published as a WADC Technical Report first in January 1955 and revised in October 55.

(3) Volume I of 3 of "Techniques for Application of Electronic Component Parts

in Military Equipment", published in January 1957 as WADC Technical Report 57-1. The next volume should be ready for distribution at the end of January 1958 and the last one by mid-1958. Although published by the Air Force, the Army and the Navy contributed a large portion of the information.

In summary the Air Force reliability program consists of several concurrent phases. The first can be termed as "advancing the-state-of-the-art"; the purpose of the second is to modify all equipment specifications so that they will include definite reliability requirements and methods of evaluation to show whether these requirements have been met. The goal of the third phase is to insure the use of the best component parts in the maintenance of Air Force equipments.

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RELIABLE DESIGN AND DEVELOPMENT TECHNIQUES

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Summary

Mechanical concepts must be applied to modify electronic circuit design in order that large scale computer equipment can attain practical levels of reliability. This paper cites some specific mechanical design problems with regard to the reliability of a particular computer system, the AN/FSQ-7.

Introduction

Electronic components, no matter how good their quality, will not perform properly unless placed in suitable environments. Military specifications are explicit with regard to operating conditions or performance guides to ensure reliability, but they cannot cover special problems which arise from particular circuit designs. Therefore, the mechanical engineer must derive a unique solution for each new problem.

Prior to the actual mechanical design, the engineers, designers, and draftsmen must clearly understand the system aspects of the particular reliability problem they are attempting to solve. They must be aware of the effect the solution to their problem will have on the overall system with regard to reliability and possible electronic design changes caused by mechanical modifications. They must be sure that any modification they may request will not place the operation of the computer system outside the allowable specification limits. Mechanical designers should, therefore, be furnished with detailed specifications which have already been reviewed by reliability personnel in a systems group.

Portions of these specifications should be prepared by mechanical engineers who strive to answer essential design questions as completely as possible ahead of time. These questions would concern levels of pluggability, details of circuit package construction, method of power distribution, module layout and arrangement, environmental conditions, back panel wiring and cable terminations, cooling system construction, and locations and style of test points and indicators.

The mechanical engineer must consider the overall reliability as well as the overall purpose and functions of the system. For example, in providing a rotating magnetic field for a cathode-ray display tube, he may find a simple mechanical system will have higher reliability than an all-electronic system requiring a large number of tubes and components. The mechanical system has the added advantage of being far more predictable with regard to performance, life expectancy, and environmental conditions required to perform a specific function.

Specific Design Problems

The specialized nature of the AN/FSQ-7, and the Air Defense System for which it was built, caused specific design problems which had to be solved within the needs of the system.

Mapper Console

A display mapper console was designed to show target information generated at a remote radar site. Information is transmitted over telephone lines to a cathode-ray tube in the mapper console. Since the cathode-ray tube deflection coil and a magnetic drum in the mapper console must be driven in synchronism with the radar antenna, they must repond instantly to changes in angular velocity caused by wind effects on the antenna.

The main design difficulty lies in the fact that only limited power is available over the phone lines to drive the components in the console. For reliability purposes, the tube count in the amplifier must be kept to a minimum; therefore, the maximum torque available to the synchronous drive motor is only seven ounce-inches. One pulse per motor revolution is available from the phone line. Drive power is so low that auxiliary 60-cycle power, controlled by a centrifugal switch, is used to put the unit into operation.

The input mechanism includes a synchronous drive motor, a centrifugal cutout switch, the magnetic drum, three magnetic brakes, two differentials, a photo-cell timing slit, a cam-operated switch, reduction gears, a universal drive shaft, and the deflection coil. The total inertia reflected by the complete system to the drive motor is 0.632 ounce-inch-seconds^2.

Friction. Because of the low torque available, the friction within the system must be kept to a minimum. The problem of reducing friction is further complicated by the undesirability of using a gear tooth lubricant. Possible contamination of the lub-

ricant could increase friction and could hamper the operation of the photo cell in the gear box.

To ensure that friction will not increase during the 10-year life expectancy of the gear box, an unusual gear design was chosen. By using hardened stainless steel gears with an exceptionally smooth tooth finish, it is possible to keep friction torque down to a value of 2.8 ounce-inches, leaving a safety margin of 2.5. For gear material, type 440-F-SE stainless steel was selected. All gearing is class 2 precision, and the gears are hardened to Rockwell C-60. The gear teeth are formed by grinding to a surface finish of eight micro-inches. Fifty class 5 ball bearings, supporting all rotating parts, are pre-lubricated with Andok-C grease, which has a predicted life of 10 years and fulfills the lubricant requirements.

Accessibility. Since the mechanical transmission has a life expectancy of 10 years or 100,000 hours operating time, the equipment had to be designed so that the short-lived photo-cell tube was easily accessible. Therefore, the photo cell was mounted near one side of the gear box, and a special easy-access opening was provided for it, allowing an exceptionally short replacement time. The gear box cover plate was sealed with a rubber gasket to protect the unit from dust and other contamination.

Thirteen of these transmission units, comprising approximately 3,000 individual mechanical components, have had a total operating time of 200,000 hours to date. No serious malfunction has developed, and performance is satisfactory.

Repair and Replacement Time. An important consideration in reliability is the time lost for repair and replacement of components. As a first approximation, halving repair time has the effect of doubling mean free time between failures in a duplex system. This is where the mechanical engineer can make a major contribution. For example, one of the problems encountered in replacing the relatively short-lived cathode-ray tube in a mapper console is the adjustment time required to line up the deflection coils.

The particular tube used in this console has a close tolerance metal shell at the face end of the tube and a large-tolerance blown-glass neck. The center line of the neck has six degrees of freedom with respect to the axis of the metal shell. The design used to minimize tube replacement time uses three axial springs, a sliding plane surface, and a spherical seat to give the deflection coils the required six degrees of freedom.

After the tube is placed in position, a hand wheel is rotated to lock the moving surfaces together. Tube replacement time is about three minutes since there are no time-consuming, difficult-to-reach adjustments to be made by the technician.

The components in the mapper console are designed to be replaced in their entirety. Replacement time is short since disassembly and reassembly procedures are extremely simple.

Circuit Packaging

The selection of the proper package will make a firm foundation for building computer reliability and maintainability. Specific design problems revolving around these factors will illustrate this point. The package elements should contain a single basic circuit to make testing and trouble shooting easier and to permit greater standardization. The basic packages should be grouped in integral blocks so that failures can be traced to a single block. These building blocks can easily be replaced if they are designed to be pluggable, thus keeping computer downtime under 15 minutes. This ease of replacement is essential if a 10-day mean failure-free rate, or better, is to be achieved in huge systems like an Air Defense Control Center. In a basic package, lines are made as short as possible, the number of electrical joints used is kept low, and component leads are straight to make manufacturing easy. Additional design features allow for replacement of defective components individually. Heat-generating components are separated from temperature-sensitive components as much as possible.

An assembly comprising a basic circuit package called a "Q-PAC" is shown in figure 1. In the lower section are R and C components which may or may not be potted, depending on the heat transfer system and the environment. Diodes are in the next higher layer and are protected from heat by a reflecting surface. Transistors, which can be replaced individually, are clip-mounted to a plate that provides shielding and acts as a heat sink. Heat is carried off by four corner posts as well as by radiation to a cold plate cooling unit.

The basic circuit packages are plugged into an aluminum framework called a pluggable unit or logic block (fig. 2). The framework carries off heat to the cold plates next to the pluggable unit. The cold plates have a temperature of 58° Fahrenheit, and component body temperatures are kept below 80° Fahrenheit. The pluggable unit serves as a structural member and provides ground planes and shielding for the basic circuits.

The bus bars distribute supply voltages, and shielded conductors serve as signal lines. Twisted

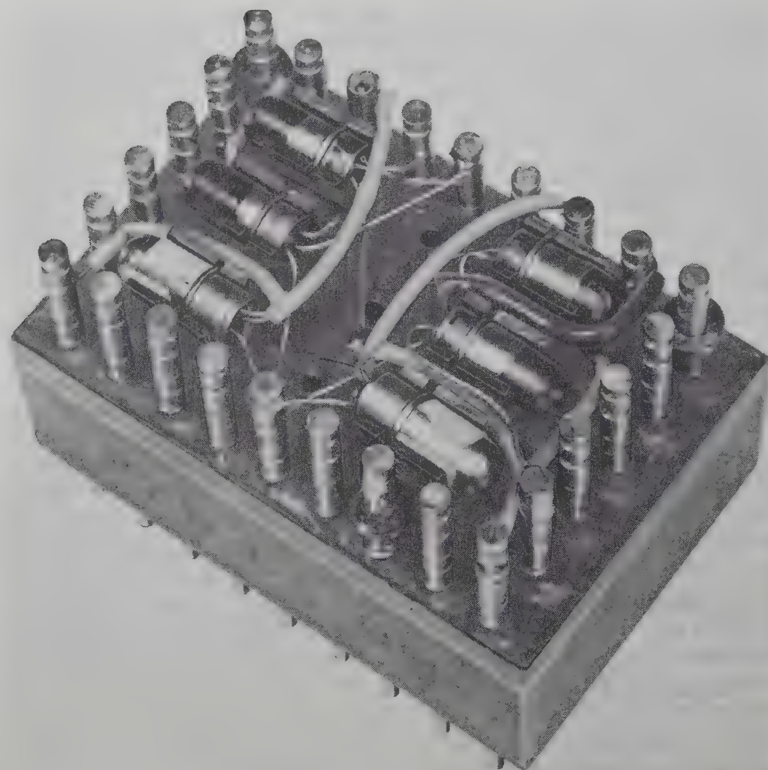

Fig. 1 - Q-Pac transistor assembly.

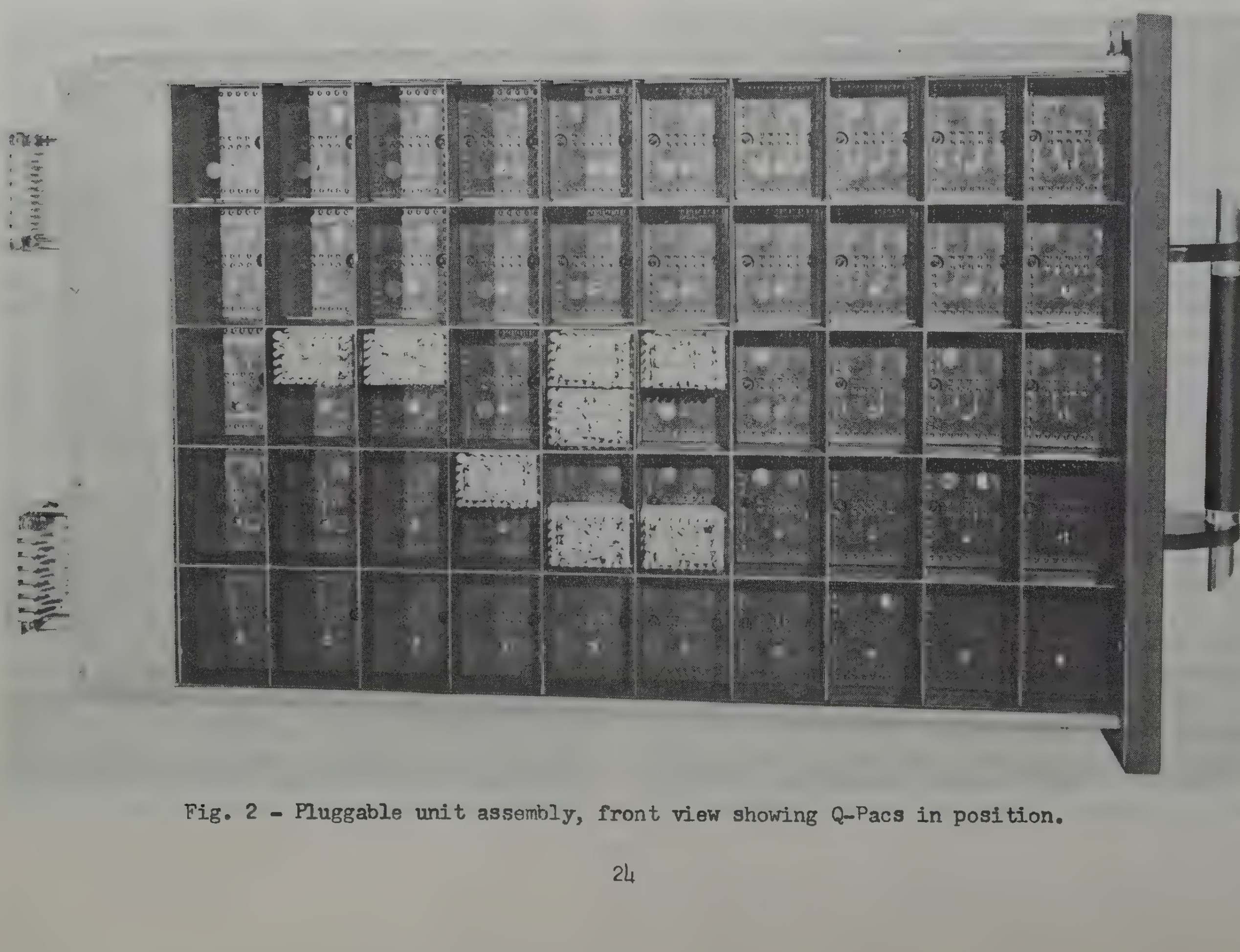

Fig. 2 - Pluggable unit assembly, front view showing Q-Pacs in position.

pairs of wires are used for critical or noise-susceptible lines (fig. 3).

Memory Drum Design

Good mechanical design can have a strong influence on memory drum reliability. Important factors to be considered here are head adjustment and bearing replacement.

Drum reliability cannot be fully guaranteed by proper arrangement and use of pre-lubricated sealed-for-life bearings. However, if the read-write heads are designed so that they do not have to be readjusted each time the drum is replaced, the reliability will increase as a result of less downtime.

Read-Write Head. The shoe of a floating read-write head is supported by a film of air surrounding the moving drum surface. The support force is generated by the moving air film, which circulates with the moving drum surface (fig. 4). This force is similar to that produced by hydrodynamic effects

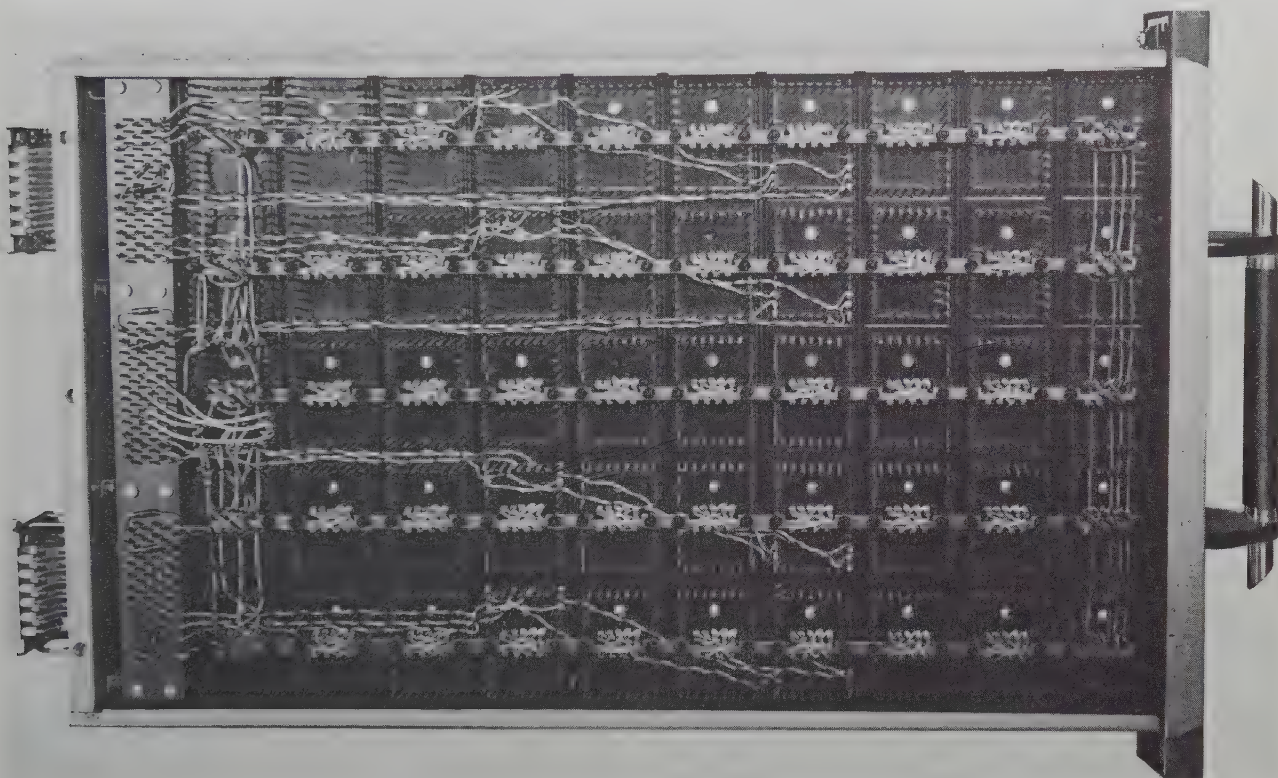

Fig. 3 - Pluggable unit assembly, rear view showing wiring.

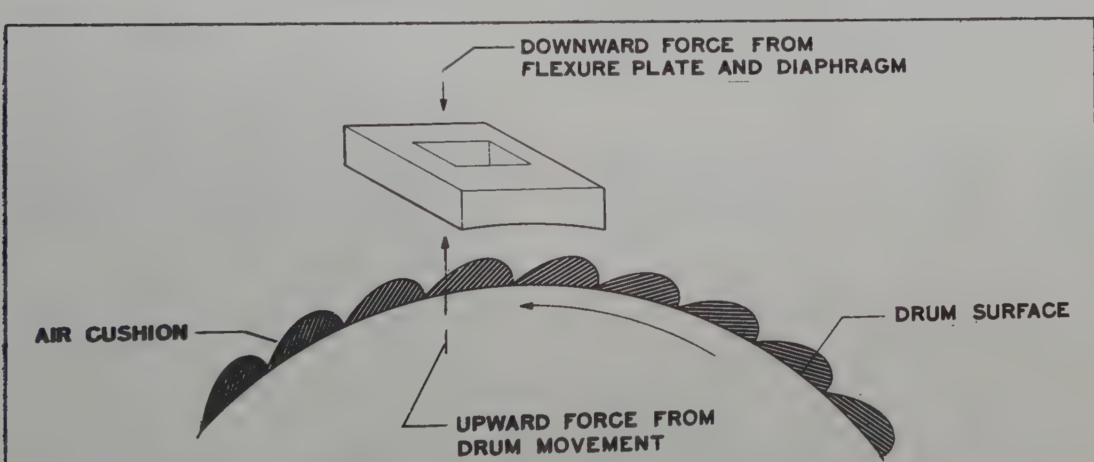

Fig. 4 - Floating shoe positioned on memory drum.

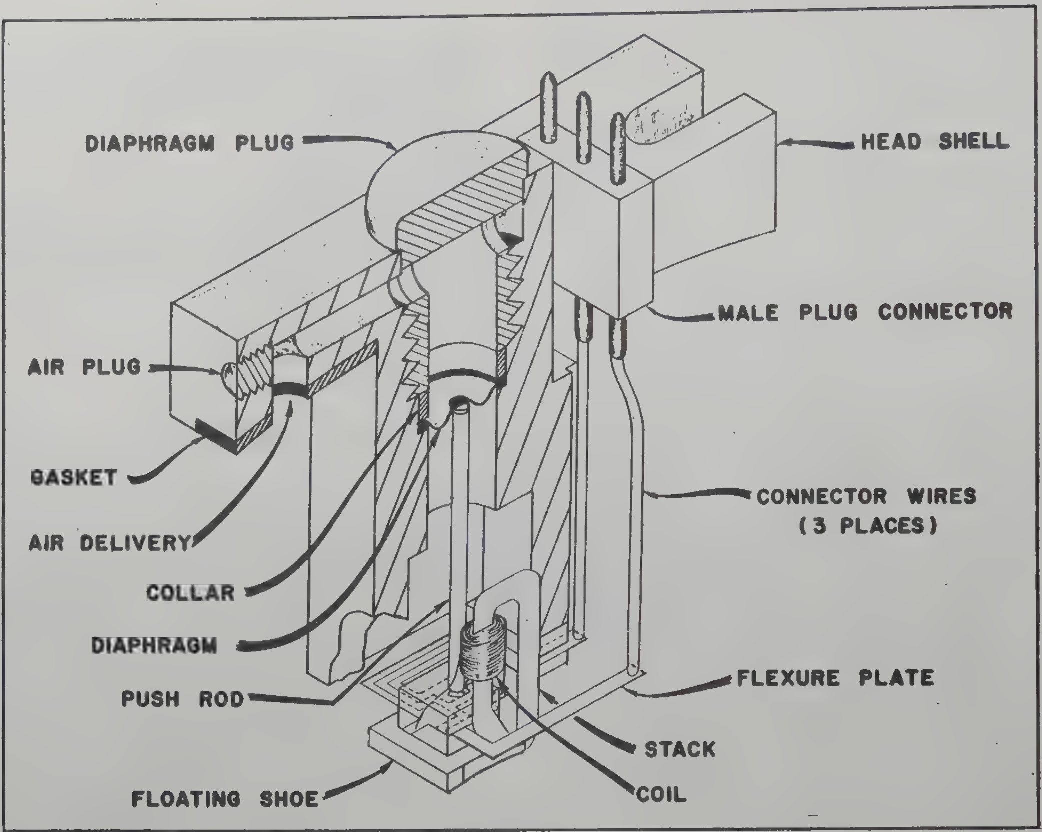

Fig. 5 - Magnetic-head cross section.

in ordinary lubricated bearings. Down loads from the head coil and laminations are balanced by the aerodynamic lift so that a small clearance is always maintained between the drum surface and the shoe.

The shoe is supported by a flexure plate so it has three degrees of freedom (fig. 5). It cannot shift out of its assigned track on the drum, but it is free to move radially with respect to the drum. Air pressure applied to the diaphragm forces the shoe downward until it is in balance with the upward force from the drum surface. Since the shoe is balanced and flexible, it can compensate for sizeable radial eccentricities in drum movement.

Whenever the drum stops rotating, reduction in air pressure through the air delivery opening causes the shoe to spring upward and not touch the drum surface. Once the drum is put back into operation, the head is automatically positioned and ready. Since previous designs required a head-adjustment time of four to six hours, this represents a major reduction in downtime.

The entire drum rotor assembly can be replaced in less than 15 minutes since the new rotor assembly does not have to be critically matched to the former installation.

Conclusion

After a specific electronic design is created, the mechanical engineer must solve the attendant problems of friction, lubrication, accessibility, repair and replacement of components so that practical levels of reliability may be attained in computer systems.

THE NAVY SPECIFICATION PROGRAM FOR RELIABILITY

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The objective of this paper is to simply relate to you the role of the specification in the Navy's Electronics Reliability Program over the past years and to outline what appears to be the specification aspect of reliability for the future. In my discussion I will deal for the most part with full equipments and systems reliability and specifications.

The Navy, as one of the services of the Defense Department is essentially a consumer agency. Yes, we have research and development laboratories; however, we must look to industry for a good part of our research and development and for all of our production needs. As a consumer agency we find ourselves in the procurement business and the specification becomes the important tool and communications link between ourselves and the contractor, design agent and manufacturer. This communications tool, the Specification, must contain and reflect all of the good engineering required, it must reflect realistically and practically all of the new design techniques and reliability techniques developed as a result of special developments, special studies and past experience. It was once stated and I believe rightly so, quote "The only real product of the design groups at the material bureaus is the specification with its attendant follow-up to assure adherence thereto."

At this point I wish to make a statement which is the fundamental philosophy to the Navy's approach to reliability. The attainment of reliability in our electronics equipment cannot be had by pronouncing the magic word or by simply stipulating in a contract clause or special separate specification that we require maximum reliability. On the contrary, the attainment of reliability is a matter of establishing realistic, practical design requirements reflecting available parts and materials, circuit techniques, mechanical and thermal design techniques. All of these shall be in consonance with manufacturing techniques. Once this specification aspect is complete it becomes the basis from which the designer and manufacturer can work to achieve the reliability required. It will be only through the good solid engineering of the designer, the ability of the manufacturer to build to the designer's detailed requirements that the inherent reliability is attained. So, we might say that "Inherent Reliability is a function of the basic design specification, the engineering executed by the designer and the workmanship and ability of the manufacturer to transform design requirements into the physical piece of equipment."

With this philosophy as a background the Navy's efforts have always been to reflect new materials, parts, techniques into their general specifications. Newly developed concepts are included in the general specifications or into the individual equipment specifications. Environmental design criteria is under constant surveillance such that specification requirements reflect the fleet operating environments as closely as is possible.

RELIABILITY EFFORTS

Reliability is not a new effort with the Navy. If we look back into history we will find many instances of specification changes to cope with naval environments. I'd like to relate my discussions to time period of 1938 to 1949; the recent Defense Department Reliability effort from 1949 to this date and then deal with 1957 and the future.

Period of 1938 to 1949. In the 1938 to 1949 era we saw the design of shock and vibration, as well as inclination machines, developed to simulate shipboard conditions. Then the Navy led a program to redesign commercial tubes to meet these stringent mechanical tests. In the latter war years we saw the Navy tube ruggedization program to obtain what was referred to as ruggedized JAN tubes. As these developments became available, they were required in revisions to our general specifications. It is interesting to note that in the past few years much has been said about the failure rate curve or failure pattern of equipments, parts and tubes. Early failure rates and debugging, constant failure rate region and wear out region are terms of the past few years. Without this more scientific background the Navy experienced a nasty problem in the early war years. The sonar equipments

installed in the fleet experienced very high failure rates in the first few months of operation. As an emergency corrective measure, the general specification was amended to call for a new continuous operating twenty-one day life test for all prototypes. The object of the test was to debug the prototype, to detect the marginal circuits and parts. This was found to be very effective. The 1946-1951 period saw another concentrated effort on increasing the reliability of tubes and in 1952 the requirement for use of the higher quality Navy Reliable tube line in all new Navy electronic equipments.

Period of 1951 to 1957. The era of 1951 to date we might say was an era of increased emphasis in reliability with the U. S. Navy. The effort was planned and coordinated in implementation of recommendations of the Ad Hoc Group on Reliability of Electronics Equipment published as the Progress Report on Reliability of Electronics Equipment 18 February 1952. (This group later became the Advisory Group on Reliability of Electronics Equipment (AGREE) presently sponsored by the Office of the Assistant Secretary of Defense (R&E)). The 1952 to 1956 era saw a rigorous review of electronics specifications with reliability as a basic objective. For example let us review the Bureau of Ships Specification Effort.

(A) With respect to specification for design MIL-E-16400 "General Specification for Electronics Equipment (Ship and Shore)" This specification represents a drastic revision of specification 16E4.

(1) Environmental criteria were carefully reviewed to make design requirements more realistic. In lieu of all design for the entire excursion of -54°C to +65°C, four temperature classes were established:

Class 1. -54°C to +65°C for Shore Exposed Equipment
Class 2. -28°C to +65°C for Shipboard Exposed Equipment
Class 3. -40°C to +50°C for Shore Sheltered but Unheated Installations
Class 4. -0°C to +50°C for Ship/Shore Housed and Heated Installations

(2) The new MIL-STD-242 (Ships) became a part of MIL-E-16400 to indicate Selected Standards and Preferred Parts. This document included new commercial parts approved for use but not covered by military specification due to time required to establish enough items to write a military specification and also to complete coordination. This document also includes application data. MIL-STD-242 is presently being made a tri-bureau (ORD/AER/SHIPS) document.

(3) The new line of higher quality Navy Reliable Tubes were introduced into this specification many months prior to complete tri-service coordination on tube requirements.

(4) The environmental tests were very carefully reviewed against environmental criteria to establish temperature tests to simulate closely actual environments. The twenty-one day life test called the Accelerated Life Test was shortened to 15 days; however, truly accelerated features were introduced:

Test at high temperature, high humidity, cycling of plus and minus input voltage and even a periodic 15 minute break to introduce thermal shock on tube filaments.

In general all tests were revised not necessarily to make requirements more rigid but to better simulate service conditions and to obtain greater assurance of reliability.

Later revisions saw the following added to the specification

(a) Stipulation of Standard Preferred Circuit Voltages

(b) Stipulation of Preferred Circuits

(c) Preferred Dimensions for Modules of Modular Construction

(d) Introduction of Transistors

(e) Introduction of voltage and frequency transient condition requirements

(f) Reference to Design Guide Documents such as "Guide Manual of cooling methods of Cooling Electronic Equipment NAVSHIPS-900-190", the "NEL Reliability Design Handbook," the "Preferred Circuits Manual NAVAER-16-1-519"

In order to establish a specification which is more realistic and compatible with manufacturing techniques draft copies were forwarded to industry for comment prior to printing.

(B) Other General Specifications

There were other areas where new general specifications were needed and established; such as;

(1) MIL-E-17555 General Specification for Packaging and Packing Electronics Equipment and Parts.

(2) MIL-E-17362 "Military Specification, Electronic Maintenance Parts Requirements" to simplify parts provisioning and insure adequate spares for first deliveries.

(3) MIL-E-19100 "General Specification for Electronics Shipboard Trainers".

The Bureau of Aeronautics recently issued Specification MIL-E-19610. This specification was a determined positive effort to insure reliability in airborne equipments. It established reliability in terms of number of hours of equipment operation with no failures or with a specified minimum number of failures permitted. Rigid test requirements were established to obtain a measure of assurance. Very rigid incoming inspection tests and burn-in procedures for parts and tubes were devised to overcome inadequacy of parts inspection tests and poor quality control procedures.

Recently the Bureau of Ordnance, prior to the issuance of the AGREE Report, instituted a reliability program in a weapon system being developed. The program required a vigorous reliability effort throughtout the development including theoretical and experimental approaches. It utilized AGREE Task Group 4* procedures as the basis of the reliability effort. A similar action was taken by the Bureau of Ships wherein the procedures of Task Group 4 were included in a development contract for a transmitter-receiver as a trial implementation. More will be said about the AGREE procedures later in the paper.

Future Plans. I'd like now to ask the $64,000 question. What about the future? Briefly it is this: Our General specifications will introduce:

(a) Quantitative Reliability Requirement

(b) Improved equipment testing techniques, including statistically designed tests to prove compliance with the reliability quantitative requirement.

(c) More specific design criteria for improved Maintainability.

"THE PROGRAM FOR AGREE"

As you all know, the results of almost 18 months of effort by nine Task Groups on the "Program for AGREE" was recently published as the Report by the Advisory Group on Reliability of Electronics Equipment (OASD-R&E) entitled "Reliability of Military Electronics Equipment - 4 June 1957." The overall program was directed at a method of stipulating or specifying the level of reliability in a procurement document, in quantitative terms. This report was recently forwarded to the military departments for initial implementation. Gentlemen, we are on the brink of a new era!

From here on in we will treat Reliability like any other technical requirement of an equipment or system; such as power output, receiver sensitivity, accuracy, frequency stability - and reliability - all to be specified in quantitative terms and tested to the assurance required.

Thus, the impact of the AGREE Report and the following actions are planned.

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* Advisory Group on Reliability of Electronic Equipment (AGREE) Report on Reliability of Military Electronic Equipment (OASD-R&E) dated 4 June 1957.

1. Ultimately Reliability levels will be specified in all equipment contracts. Initial implementation will be on a selected basis and more or less confined to development contracts to gain experience and knowledge on the adequacy of the techniques.

2. The results of Task Group II and III are essentially the test plans that will be employed. These are based on sequential test techniques to verify compliance with the reliability level specified. Task Group II presents a plan for development or prototype models whereas Task Group III test plans apply to Pilot Line and Production Equipments. It is anticipated that these Test Plans will be edited and put into specification form for use in contracts. There are plans to include these test procedures in a handbook being sponsored and coordinated by the Office of the Assistant Secretary of Defense (S & L). This handbook will contain sampling procedures for life and reliability testing. These test procedures will in all probability supersede the BUAER equipment reliability test procedures mentioned above as part of specification MIL-E-19610.

3. Task Group IV established a "Procedure for Design and Development to Insure the Required Inherent Reliability. The Task Group report was written in the format of a Military Standard. The Bureau of Ships has already requested that this document be made a Military Standard. I should like to briefly discuss this procedure. The document assumes that the military will specify a level of reliability, most probably in terms of Mean-Time-Between-Failure and probability level with its complementary function, the Maintainability Index (Minimum % Up-Time or Maximum % Down-Time). The document provides for Phase I and II in a development contract. Phase I will be a study phase considering the entire design in the light of the many factors affecting the reliability. Figure (1) illustrates these factors. The contractor will then propose a design and estimate the reliability through prediction techniques based on parts and tube failure rates and any other available techniques specified to assess feasibility of meeting the reliability requirement. A report is submitted which will discuss or show the feasibility estimate; the report will discuss problem areas and relate planned circuit techniques; it will discuss the reliability and maintainability requirement relative to performance requirements, weight, space, cost and simplification of design. It will recommend trade-off considerations. The report will then be evaluated to modify if necessary the reliability of any performance requirements of the specification; at this time a decision will be made with approval to proceed with Phase II, the construction of the Prototype Model. As design and construction progresses better knowledge is available concerning specific parts to be used, specific parts environments, specific circuits and circuit techniques. This enables a closer calculation of the estimated reliability with better knowledge of problem areas and the need for special part developments, redundancy or other solutions. With testing of the prototype model, component units and the entire system we again are able to reestimate the reliability and performance characteristics. Again a report is submitted which will include a new estimate of the reliability and maintainability with discussion of performance, weight, space, cost and possible simplification. With this logical procedure the military procurement agency will be in a very good position to decide or evaluate release to production with a fair idea of the level of reliability, maintainability and producibility of the design.

As you see, up until now the improvements called for in specifications were in general engineering requirements. These were good and must continue. However, allied to this, the reliability parameter will be specified quantitatively and dealt with in the same manner as any other performance characteristic.

LIMITATIONS AND PROBLEM AREAS

Let me say this, all is not roses! There are problems here for the military and for the contractor. Initial cost, in the face of curtailed budgets, the need to procure perhaps a second or third model for test, time for test and availability of test facilities will plague the military especially for equipments with long mean-time-between-failures. Limited design guide information in the form of failure rates of parts as a function of application severities and knowledge of part operating environments will present a problem to contractors. I should like to mention here that presently there are two good design guide documents on parts failure rates versus application severity and environment. These are: The recently issued Vitro Report T.R. 98 resulting from Bureau of Ships Contract NObsr-63389 which supersedes in part Vitro Report T.R. 80. The other is the Radio Corporation of America Report TR-1100. RCA has granted permission to the Navy Department to reprint this

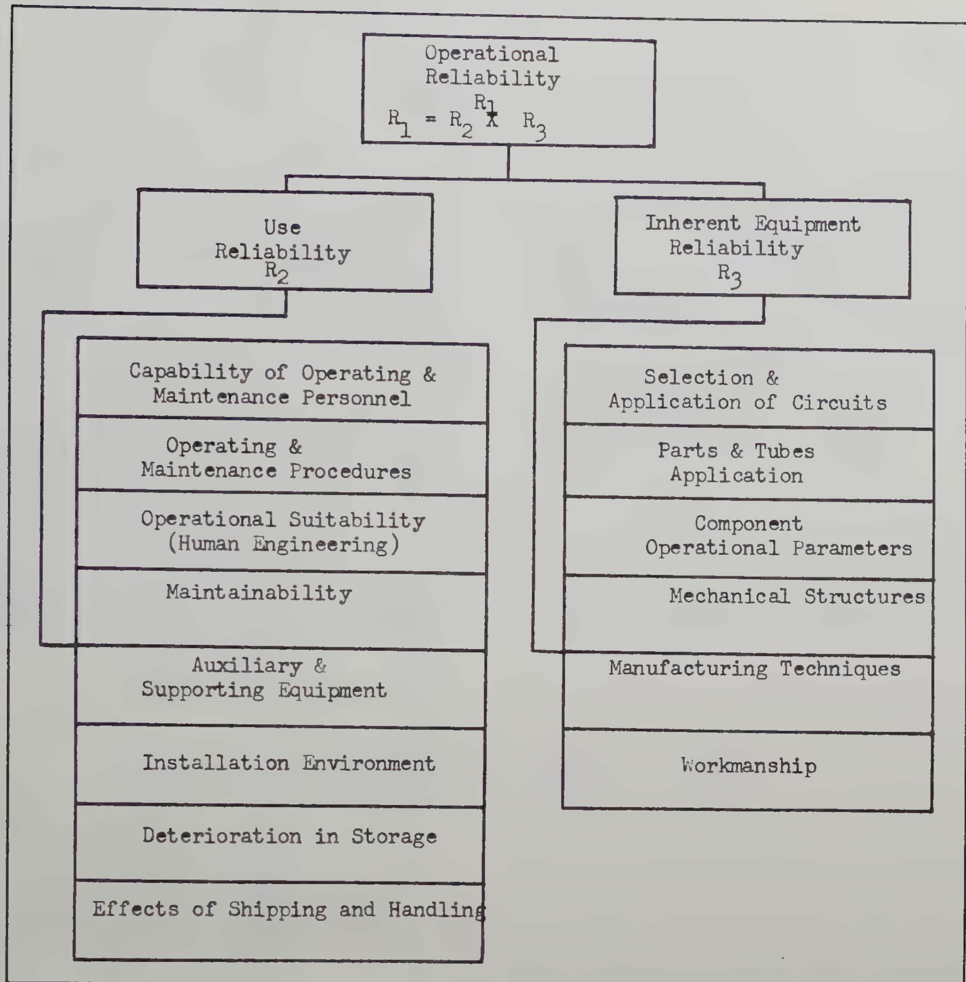

Fig. 1

document to permit availability to industry. The Office of Technical Services, Department of Commerce is being asked to reprint TR-1100 and place it on sale on non-profit basis, cost of printing.

MAINTAINABILITY

In the maintainability area I feel that much will be done in the next few years to place maintainability and its contributing elements on a quantitative basis or at least in terms of specific design criteria for improved maintainability. In the meantime, it appears that this item will be dealt with on a design objective basis with general design criteria for guidance.

FREQUENCY COMPATIBILITY

I should like to close my paper with a brief comment on a new specification requirement recently introduced. I purposely did not mention it prior to discussion of the subject of quantitative level of reliability. This requirement stems from a reliability problem not in terms of time between failures of parts or malfunctions but in terms of Frequency Compatibility when the equipment is installed or operated in the vicinity of many other equipments or systems. The increasing demand for electronics aboard ship, aircraft and at shore installations as well as more complex military operations electronics-wise has made frequency compatibility an increasingly critical problem.

Despite careful planning of frequency allocations, congestion in the limited spectrum is a problem. Over and above this, we now have radars of extremely high power output as well as receivers of greater sensitivity. These conditions are in themselves many times incompatible.

However, more than that, side lobes of transmitting antennas, and spurious radiations are disrupting communications,

guidance systems and detection systems. For years we have attempted to attack the problem on a reduction of spurious radiations basis. Minimum levels of interference were established as general design guides. However, with the increasing amount of electronics required in present military operations, it is almost impossible to clearly establish the radio frequency environment to which a design must be aimed. The reduction of spurious radiation approach is still the basic approach. However, in addition, we must know exactly what the R.F. Radiation Characteristics are of any equipment (both wanted and unwanted); we must know exactly the susceptibility or vulnerability of any receiver. With this information, a theoretical analysis of any installation or task force configuration can be made at the early planning stages.

<u>Equipment Frequency Spectrum Signature</u>. Equipments having undesired spectrum characteristics will of necessity have to be modified and can be prior to release to production. Where modification is not possible, other corrective actions may be utilized. With this problem in mind, the Bureau of Ships recently released an amendment to the Radio Interference Reduction Specification requiring that an "Equipment Frequency Spectrum Signature" be obtained on all prototype equipments. (Amend - 2 to Specification MIL-E-16910A and Amend - 1 to Specification MIL-E-16400B dated 1 November 1957).

CONCLUSION

I have tried to give you a picture of the specification area and its role or part in the overall reliability effort. A brief paper cannot fully exploit this area.

Much has been done but even more has to be done. And, here again, the words "Industry and Military Cooperation" hold more meaning than ever before.

ACCELERATED LIFE TEST IN AIRFRAME MANUFACTURE

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After listening to the various papers on reliability presented so far, I wonder how many of the people working in the electronics field have ever been associated with the development of an airplane structure. It appears to me that the philosophy followed in the engineering, quality control, and manufacture of airframe structures is of the same type that must go into the development of reliable electronic equipment. The structures group in the airframe industry is primarily responsible for the development and reliability of structures. Their responsibilities are as follows:

1. Make the theoretical calculations required to establish the loads which the structure will be required to handle.

2. Evaluate existing materials to determine which, if any, may be adequate to do the job. This is always accomplished by tests, and design allowables are established as a result of these tests.

3. Evaluate the structural design to determine adequacy. Where the design is redundant or a new structural principle is involved, tests are always performed to determine the design's adequacy. The strength of the part is always at least one and one-half times that of the design allowable under the environment to which it will be exposed.

4. Prove to the satisfaction of the company and the customer that the strength and reliability of the final product is adequate. This, again, is accomplished by tests.

5. See that adequate steps are taken to provide the necessary means for maintaining quality.

6. See that adequate repair procedures are developed. They must be such that the quality of the structure is not affected. Again, the adequacy of the repair methods are established by tests.

All of us agree that costs are important. Now, the cost of development is rising at an alarming rate. If sufficient attention is not paid to the phasing, organization, and execution of development programs, costs will be prohibitive in the not-too-distant future. Therefore, it must become as much the responsibility of the engineer to keep costs down as it is to develop good equipment. He can do this, provided he approaches his development program in a logical manner.

Determine whether each small component is satisfactory for use prior to assembling it into the next larger, more complex assembly. Test your subsystems before completing the whole system. Be sure that the complete system has an excellent chance of working in the environment to which it will be exposed. Don't baby it! Make certain that your detail designs are under the surveillance of experienced, mature engineers. In the illustrations that follow, I shall show you the general engineering approach and some of the main tests involved in designing a reliable airplane structure at the Fort Worth Division of Convair.

In every program there are four phases which must be accomplished. Sometimes one or more of the phases have already been performed. Figure 1 depicts these four phases. Phase one is basic research; phase two is applied research; phase three is engineering; and phase four is production. In the basic research phase, we are seeking an understanding of the fundamental laws of nature. This type of research should not be directed. At the time the work is done, there should be no thought of profits or possible use of the information. This work should preceed the applied research phase by five to ten years.

During the applied research phase, we are seeking application of the knowledge gained of the fundamental laws of nature to the development of materials and processes. This phase must be directed, and it should at least preceed the engineering phase. The engineering phase consists of the incorporation of the new materials and processes into a suitable design and the development of production methods. The production phase, of course, consists of making the article.

It will be noted that one man in fundamental research supports approximately ten men in applied research, a thousand men in engineering, and fifteen thousand men in production. It is not difficult to see that any time the phases of fundamental and applied research overlap those of engineering and production, the program is going to be much more costly than if each phase is accomplished in proper sequence.

The first thing which should be established in any development program is the environment. Figure 2 shows the magnitude of the environment plotted against time. If one knows the velocity and time, one can then determine the acceleration to which the equipment will be subjected. Altitude vs. time gives an indication of the rate at which pressure differentials on equipment and structure may occur. It will also give an indication of the effect of altitude on materials, etc. Temperature vs. time is one of the most important parameters, since this will give an indication of the design allowables which can be used for the structural materials. Load on the structure vs.

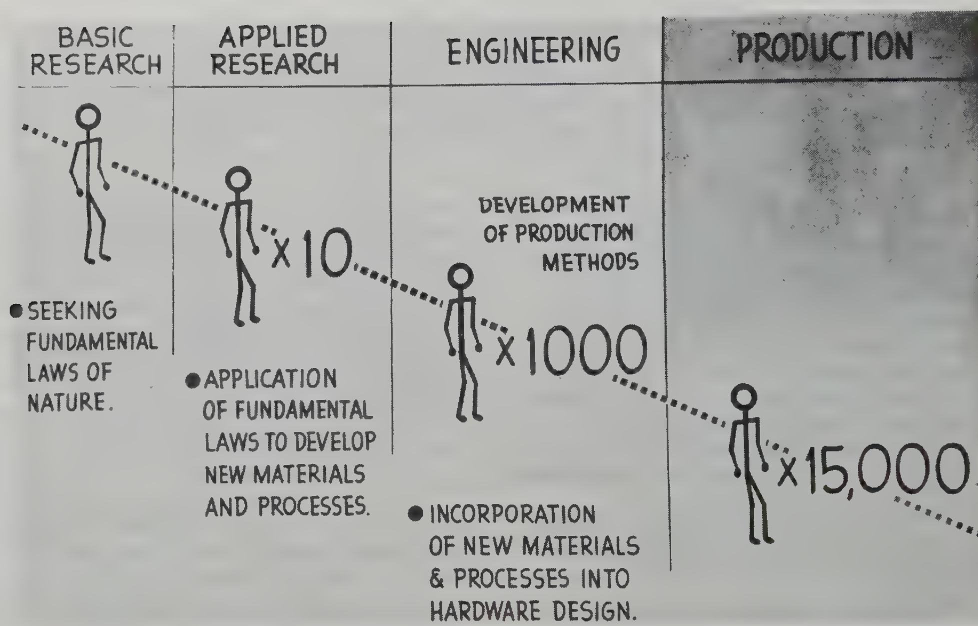

Fig. 1 - Economics of development.

time, coupled with the temperature curve, determines the structural requirements. Noise, load reversals, give an idea of the vibration and fatigue requirements of the structure. With the information shown in Fig. 2 and a knowledge of the number of the environmental cycles the structure will be required to stand, the engineer can begin developing a reliable structure.

Figure 3 shows the general type of information which the structures people require. I believe the figure is self-explanatory. In keeping with the economics of testing which I previously mentioned, Fig. 4 shows the relative cost of testing a large number of small components and gradually building up into more complex components until the final article is built and completely tested. In the first part of the development program on the B-58, there were approximately 40,000 small specimens tested (base line of the chart on the left) to determine the adequacy of adhesive and core. Sixty adhesives were screened. Ten of the adhesives which passed the screening test were given a full evaluation test, and three of the ten passed. Two of these adhesives were selected, according to availability and cost, to be used in the future

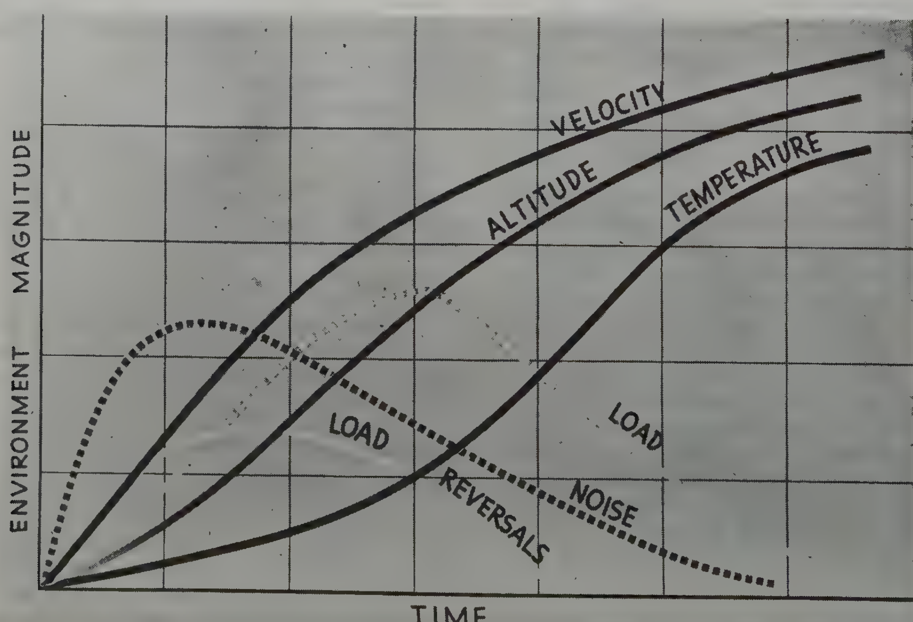

Fig. 2 - Environment.

REQUIRED MECHANICAL PROPERTIES

- ULTIMATE TENSILE STRENGTH
- TENSILE YIELD STRENGTH
- COMPRESSION YIELD STRENGTH
- CREEP AND RUPTURE PROPERTIES
- THERMAL STABILITY
- NOTCH PROPERTIES
- STRAIN RATE PROPERTIES
- BEARING AND SHEAR PROPERTIES
- INSULATION

Fig. 3

development of the sandwich panel structure. At the top of the chart on the left, there is only one article, the completed airplane. The chart on the right depicts a jar of varying diameter. This indicates the number of dollars which must be thrown into the pot to support the test program shown horizontally in the chart on the left. Note how rapidly the cost increases when the final article is being built and tested. How many final articles could you afford to build and test to prove your design?

The screening tests are shown in Fig. 5. These tests are selected to eliminate as many unsatisfactory materials as possible prior to full-evaluation tests. In this way large sums of money can be saved. The drawing on the right shows the type of test sandwich panel which is produced to obtain the test specimens necessary for screening tests. This same type of test panel is used in the full-evaluation tests. By using a panel of this size, it is possible to cut from a single panel test specimens for all the various types of tests. It tends to minimize the possibility of obtaining misleading data from any one particular test. Also it provides a standardization of procedures, so that all evaluation tests are accomplished in the same manner.

After the materials have passed the screening test, they are given the full-evaluation tests which are shown in Fig. 6. These tests are more rigorously run than the screening tests and are more complete, as shown by the environments and typical tests in the figure.

Having selected materials which will perform satisfactorily in the environment and under the load conditions to which the structure will be subjected, the materials are put together in a typical design. Figure 7 shows the elements of a typical sandwich panel. This type of structure is chosen for several reasons. It permits the use of thin metal sheets at high stresses, for all metal is effective in bending and is nonbuckling. Because the nonbuckling feature is effective in all directions, it resists thermobuckling. The panel is very fatigue resistant, since it is stiff and has a minimum of fasteners. And this panel has another property which is interesting to designers in that it provides insulation, because the core material is made of Fiberglas honeycomb. The sandwich panel as shown in the figure is framed with aluminum slugs. The Fiberglas honeycomb core is placed in between the framing. Aluminum alloy facings are bonded to the core and the aluminum slugs. All metal-to-metal bonds occurring at attachment lines are made with a nitrile rubber phenolic adhesive which is fuel tight. All facings-to-core bonds are made with an epoxy phenolic adhesive.

To determine the fatigue characteristics of the metal-to-metal bond, a fatigue machine such as the one shown in Fig. 8 is used. The specimen is loaded and then vibrated. The metal-to-metal bond is cyclic axial loaded to 600 pounds per square inch at a rate of 3,600 cycles per minute. This is continued for 10^6 cycles or continued to

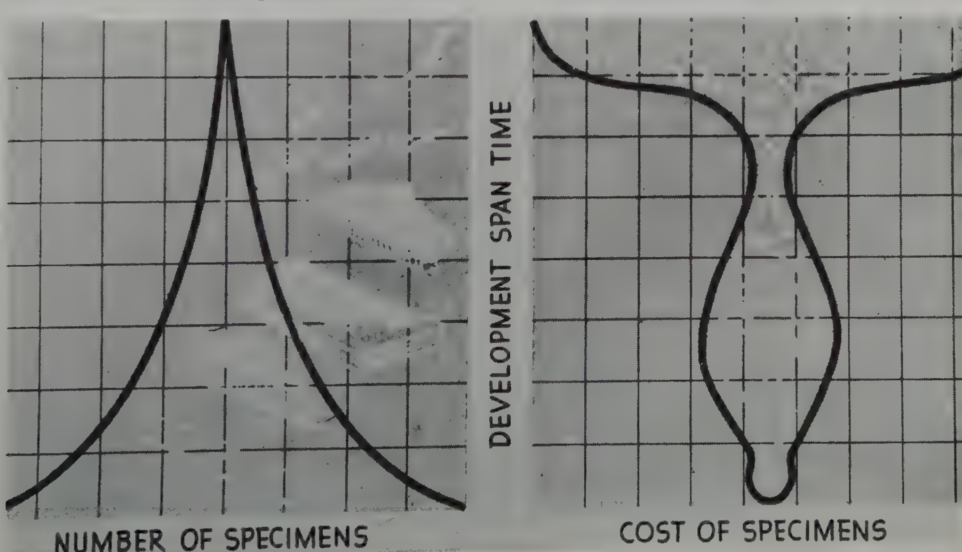

Fig. 4 - Economics of test specimen.

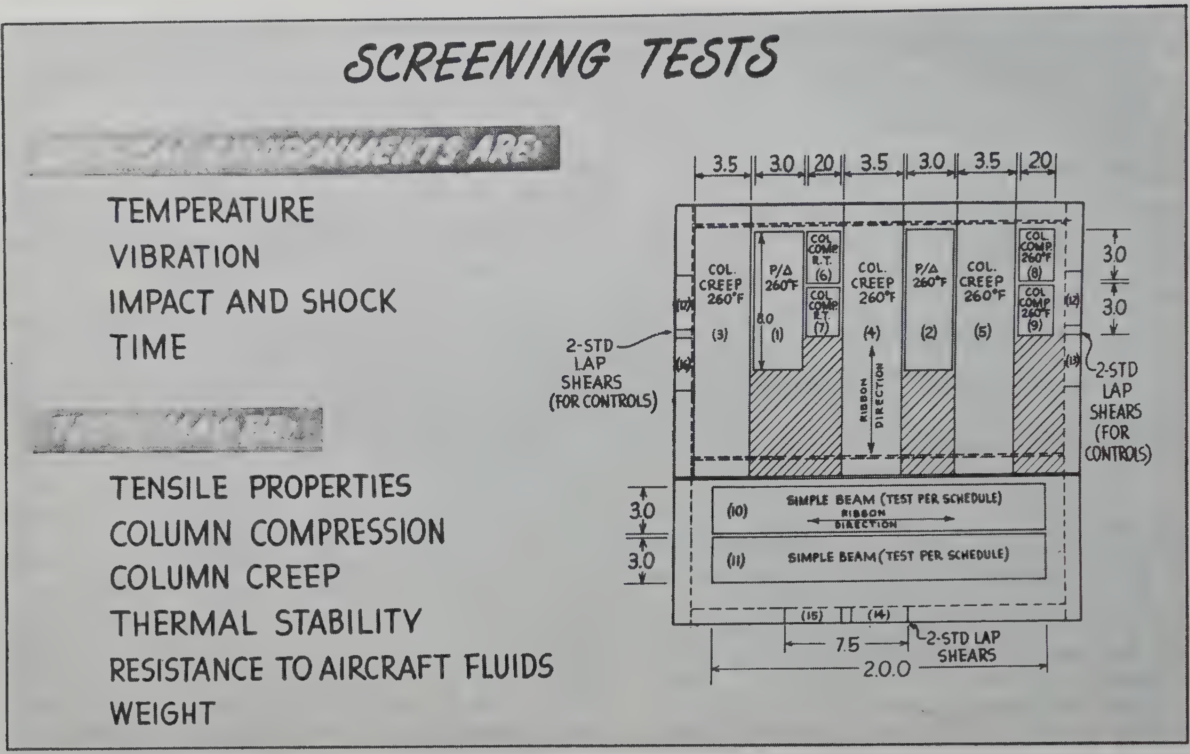

Fig. 5

failure. These tests are run at both low and maximum temperatures and room temperature. This is accomplished by putting an insulated box around the specimen and either cooling or heating as required. Figure 9 shows a setup for a simple beam test, which provides information on the flexural properties of the specimen. Again, these tests are run at both high and low temperatures.

To evaluate the peel strength of the adhesive, a test is run which is called the "monkey on a string test" (Fig. 10). It employs a drum with straps around each end so that, when one face of the specimen is attached to the drum and then placed in a tensile test machine as indicated in the figure and a load is applied, the drum tends to rotate. This peels off the one face and the drum climbs up the specimen. The load required to cause this peeling action to take place is called the peel strength. This test is run at all temperature extremes and room temperature. The peel strength of an adhesive is generally much lower at low temperature than it is at room or high temperatures. Peel strength is quite sensitive to improper manufacturing procedures, especially with those using contaminated surfaces.

The small size of the compression test specimen shown in the test fixture (Fig. 11) again depicts the attempt to save both time and money by keeping the specimen sizes as small as possible during early testing. Again, this test is conducted at both high and low temperatures and at room temperature.

Before the adhesive and core material can be used in sandwich construction, it is necessary to find the effect, if any, of aircraft fluids on their physical properties. Figure 12 shows a typical setup for the exposure of test specimens to aircraft fluids. Each of the glass containers is filled with one of the aircraft fluids, such as fuel or hydraulic oil. The specimens are placed in the container; an insulated cover is placed on the fixture; and the temperature is maintained at 140°F. At the end of the first week, and each succeeding week thereafter for a total of four weeks, eight specimens are removed and tested and their physical properties are compared to control specimens. During the next eleven months,

(continued on page 40)

EVALUATION OF MATERIALS WHICH PASSED SCREENING TESTS

	TYPICAL TESTS
TEMPERATURE	BEND STRENGTH
VIBRATION	LAP SHEAR TESTS
AIRCRAFT FLUIDS	PEEL TESTS
HUMIDITY	CREEP RUPTURE
SALT SPRAY	SIMPLE BEAM TESTS
RADIATION	CONTROL TESTS
TIME	REPEATABILITY
	PRODUCIBILITY
	FATIGUE
	FLOW

Fig. 6

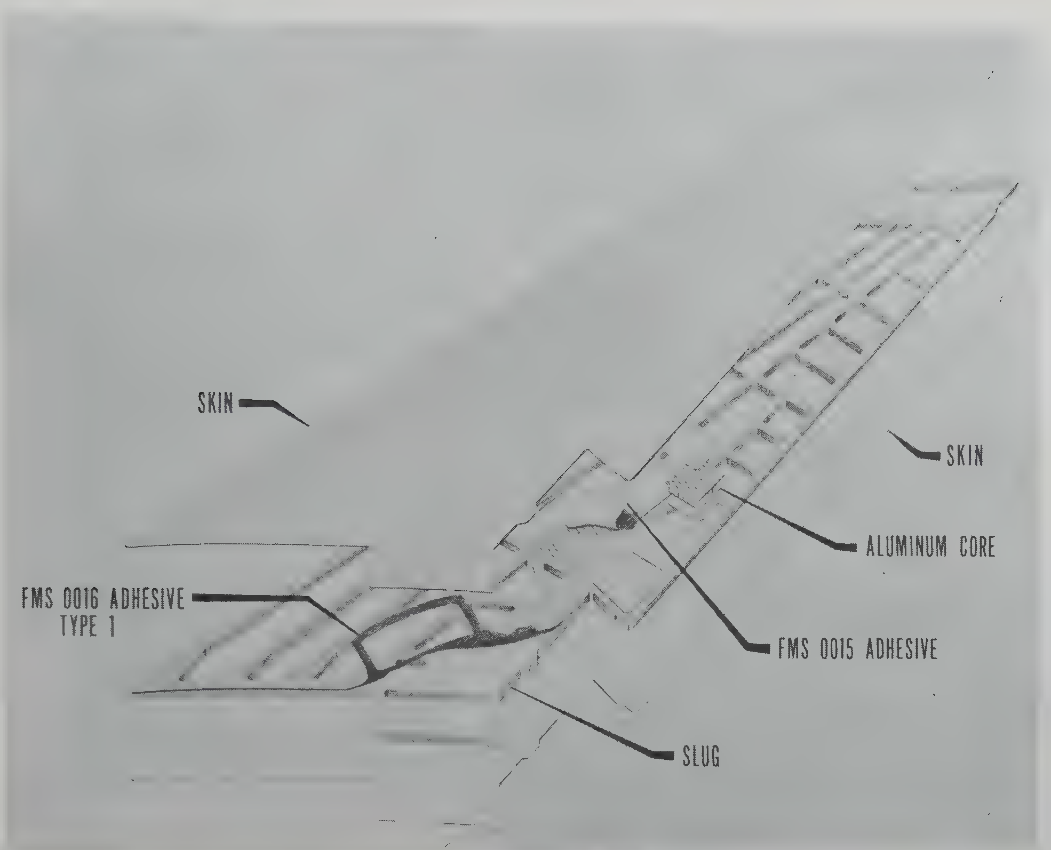
SKIN
SKIN
ALUMINUM CORE
FMS 0016 ADHESIVE
TYPE 1
FMS 0015 ADHESIVE
SLUG

Fig. 7

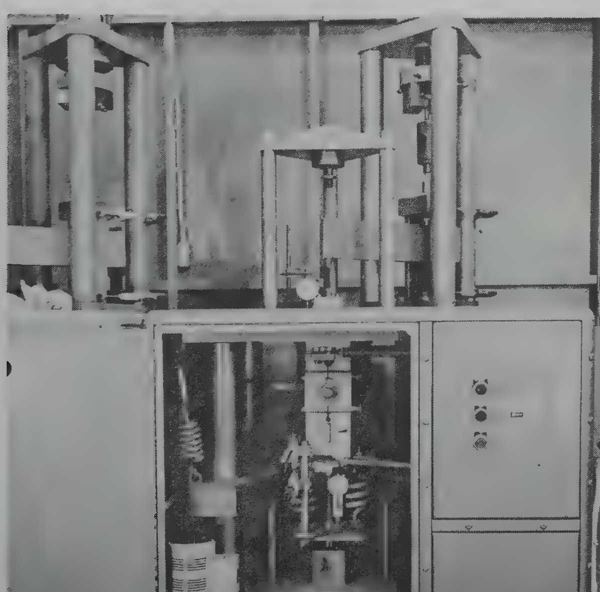

Fig. 8

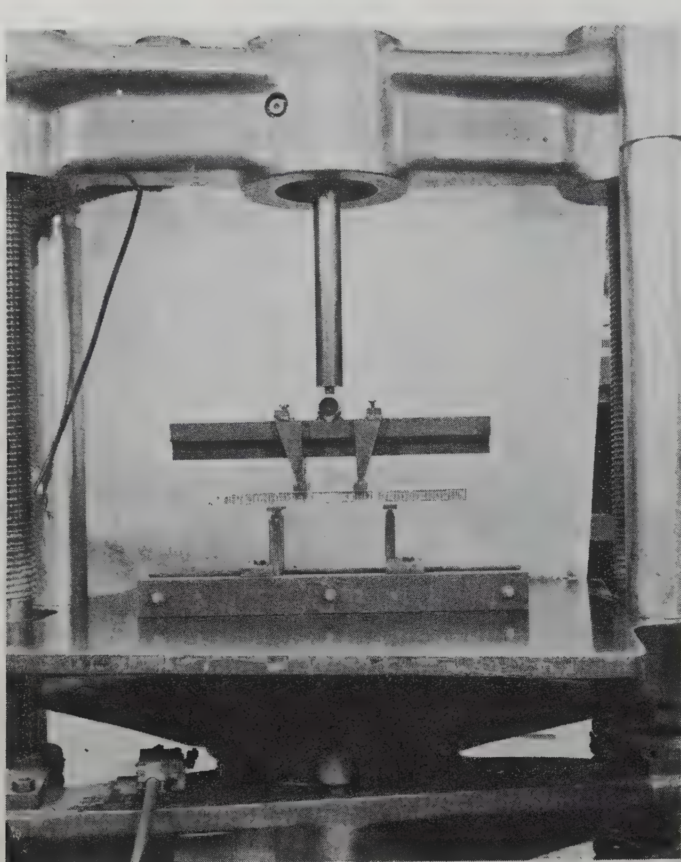

Fig. 9

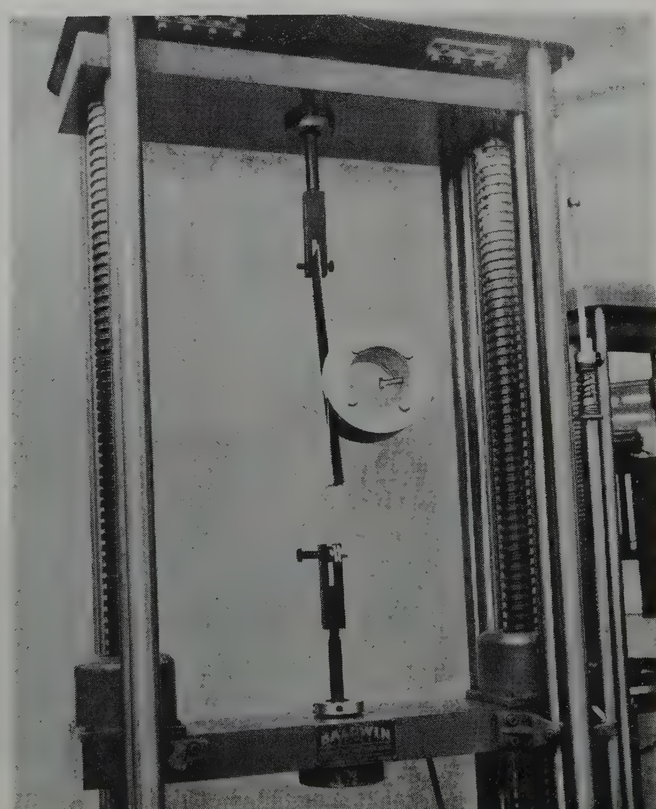

Fig. 10

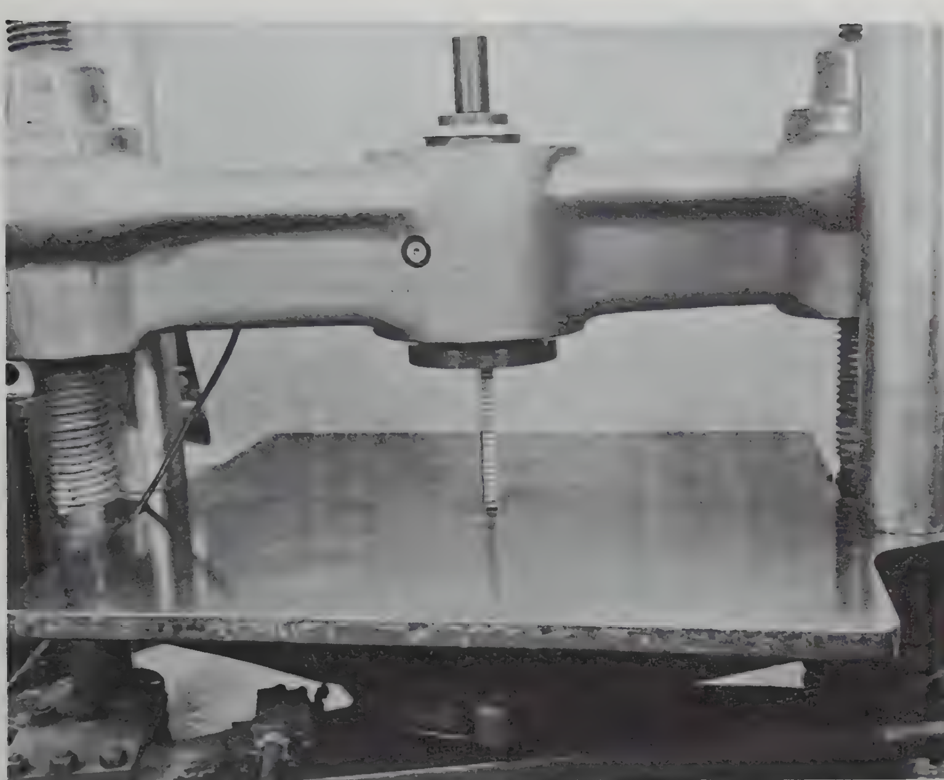

Fig. 11

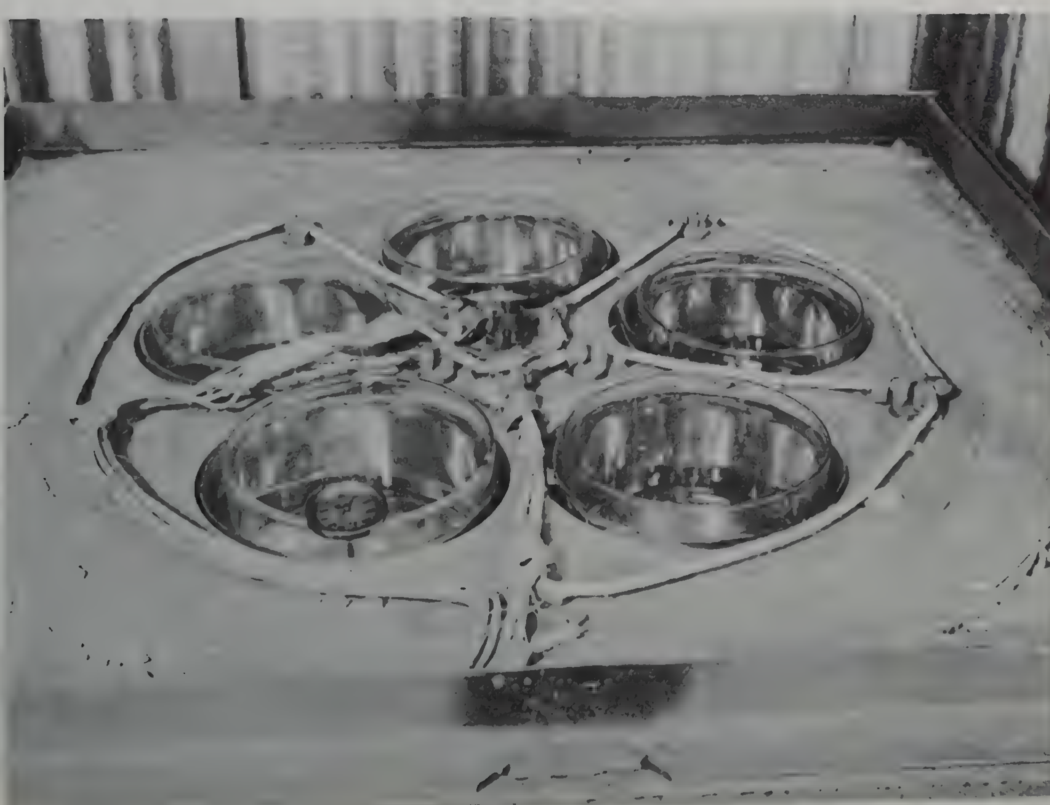

Fig. 12

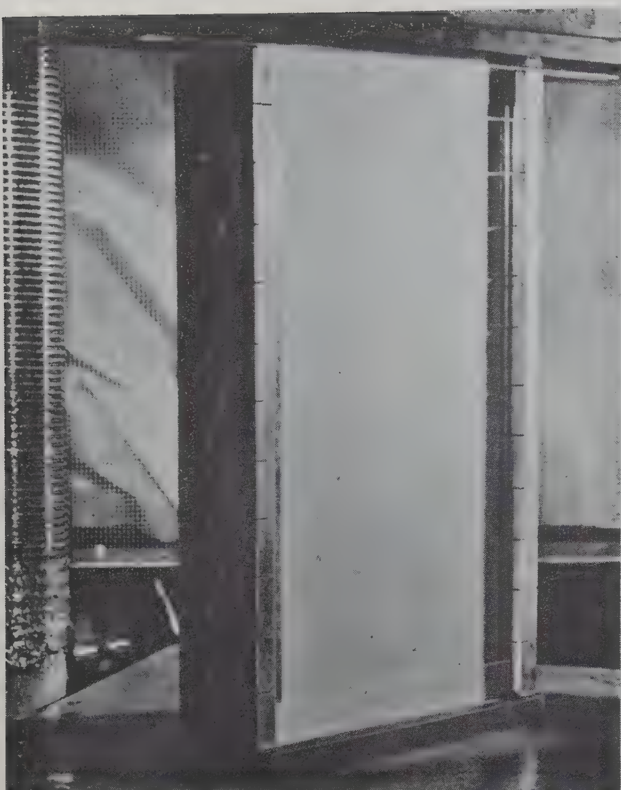

Fig. 13

(continued from page 36)
eight specimens are removed each month and tested in a similar manner. Thereafter, eight specimens are removed each year until a total elapsed time of five years has occurred. All specimens are tested in the same manner, both at low and high temperatures and at room temperature.

After the preliminary tests have shown that the materials and type of construction appear to be satisfactory, larger specimens are made. The specimen shown in the test fixture in Fig. 13 is ½ inch by 21 inches by 23 inches. The test shown here is a column compression test. During these tests on the sandwich panel construction, the adhesive originally chosen was found unsatisfactory in creep property. Therefore, it was necessary to use the more costly adhesive which had passed the evaluation test and had not been selected because of its availability and higher cost. This adhesive proved to be satisfactory.

The next step is to produce the first full-size panels, by production methods. They are 23 inches by 69 inches by 0.5 inch. The test shown in Fig. 14 is called the "Iron Maiden test." The test panel forms one face of an iron box, and is so jigged that it is free to move, yet will seal so that air pressure can be applied to the inside face of the test panel. The specimen and jig is then placed in the 600,000 pound test machine. The panel is preloaded, brought to the necessary temperature and internal pressure, and then loaded in compression to failure. During some of these tests, the surface exposed to the inside of the box is maintained at a temperature of -100°F while the external surface is brought to maximum temperature at a predetermined rate. The external surface is heated with banks of quartz Tunsten GE lamps. In some instances ultimate design loads are applied at maximum temperature for periods of up to 200 hours to determine creep properties of the sandwich panel.

Probably one of the most valuable tests is the wing box beam test, shown in Fig. 15. This test is designed to represent a portion of the wing. For the first time both bending and sheer stresses are introduced simultaneously into the sandwich panel. The entire specimen and jig is placed in an insulated box having an insulated lid. The ratio of the bending stress to the sheer stress is adjusted by use of the four rams shown in the illustration. During some of the tests, design loads are held on the specimen at maximum temperature for 200 hours. This gives an indication of the amount of creep the structures engineer can expect under the same conditions in an airplane. In one series of tests, the internal surface is held at -100°F, while the external surface is held at maximum temperature. In all instances, the test is terminated by loading the structure to failure.

With the advent of high-power jet engines, noise became a problem. The horn of an air siren and specimen holder is shown in Fig. 16. This siren is capable of producing a sound pressure level of 170 db. Conventional structure would last only a few seconds or minutes in this noise level. The sandwich panel type structure is not affected over long periods of time; therefore, it is being utilized on the B-58.

The question always arises as to what are the long-term weather effects of fuel in contact with

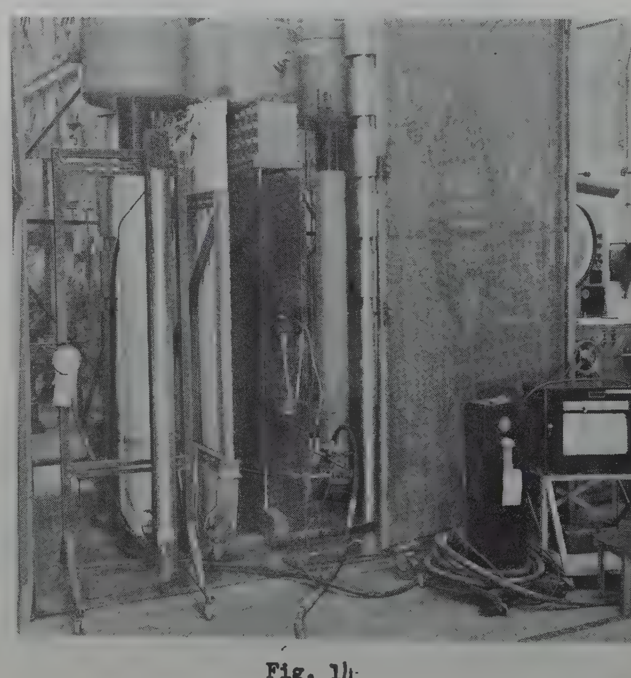

Fig. 14

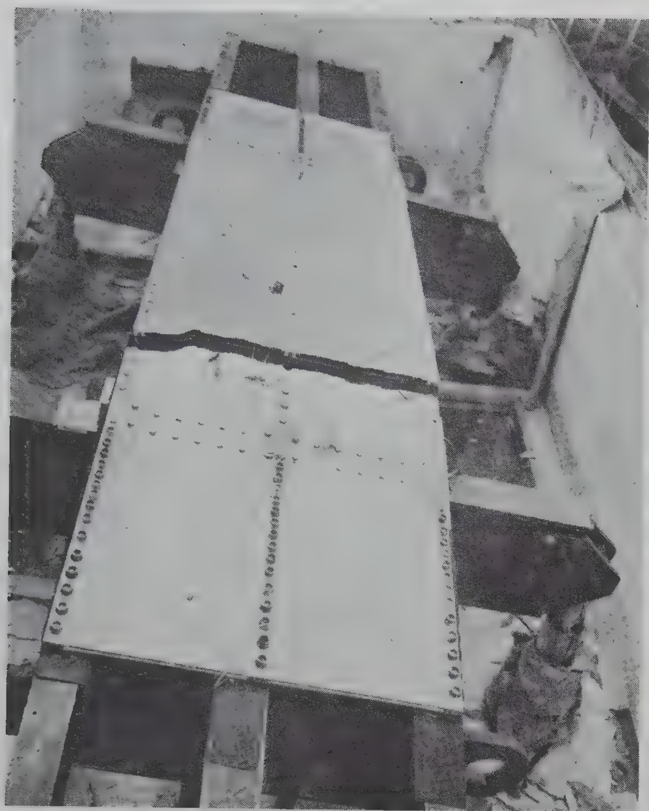

Fig. 15

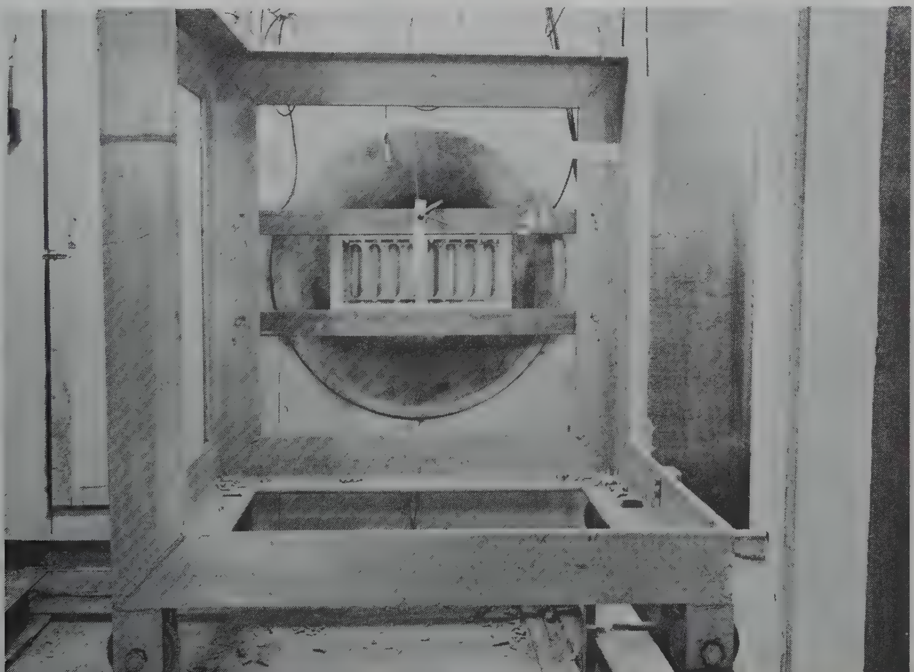

Fig. 16

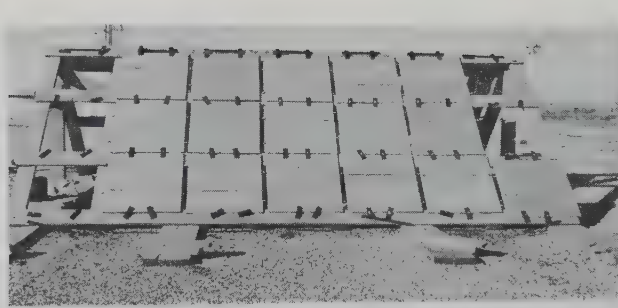

Fig. 17

the adhesive and core material. To answer this question, Convair makes several specimens which are 24 inches by 24 inches by 0.5 inch with a picture-frame integral slug system. The panels are internally filled with JP-4 fuel and exposed on a jig at a 45 degree angle facing south (Fig. 17). One panel is removed annually and tested in column creep, simple beam, column compression, and lap sheer. These tests are continued over several years.

In order for the structures people to evaluate their theories and substantiate their calculations of a redundant structure, they must build an elastic model. The elastic model is similar in nature to the bread board of the electronics engineer. From this model, which is very complete as far as geometry is concerned, the structures engineer determines the elastic constant of the structure and the distribution of loads under various loading conditions. The load distribution, Fig. 18, is determined by approximately 2,400 strain gages throughout the model. The model is placed in the jig upside down, so that loads can be applied using calibrated lead weights supported on hangers. The results obtained from the elastic model are compared to other structrual tests on components and ultimately to those obtained from the final static test airplane.

Since the sandwich panel is going to be used to form the sides of an integral fuel tank, it is necessary to evaluate it for this purpose. Figure 19 shows a portion of a wing fuel tank, which is placed in an insulated box so that the temperature can be controlled. It is jigged so that various loads can be applied which simulate the worst loading conditions expected on the aircraft. These loads are cycled the same number of times they are expected to occur during the life of the airplane.

Figure 20 is a test designed to evaluate the wing tank to determine its ability to handle

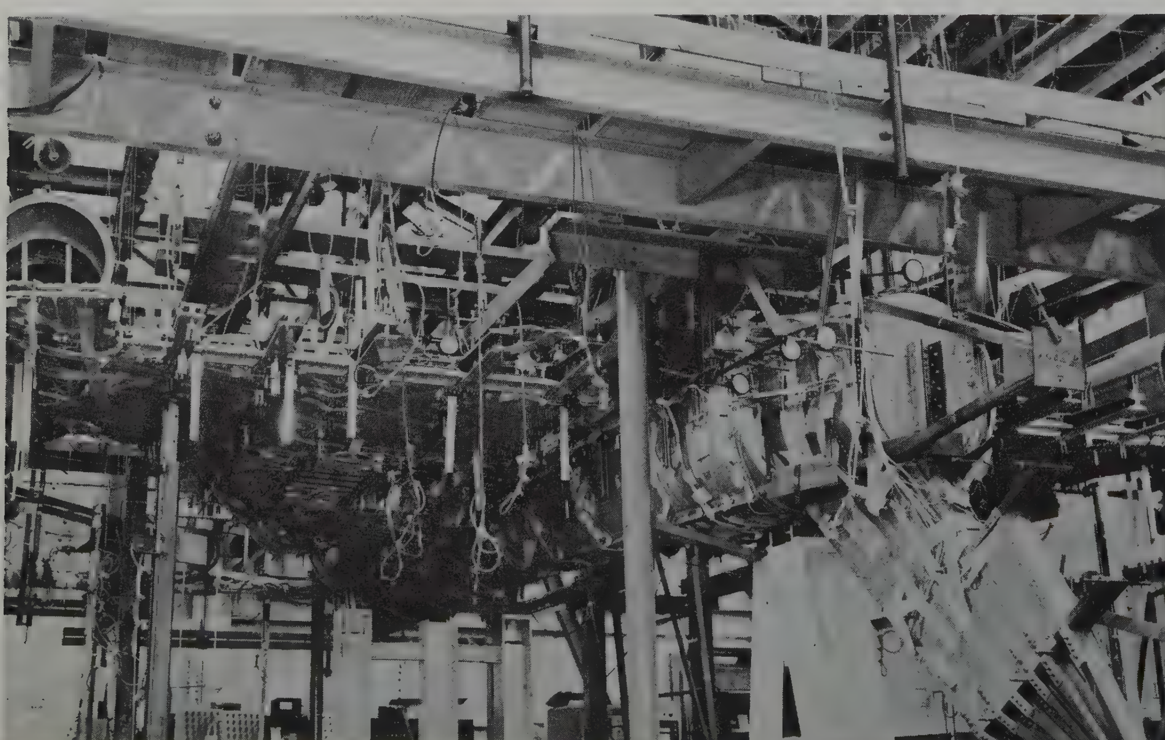

Fig. 18

Fig. 19

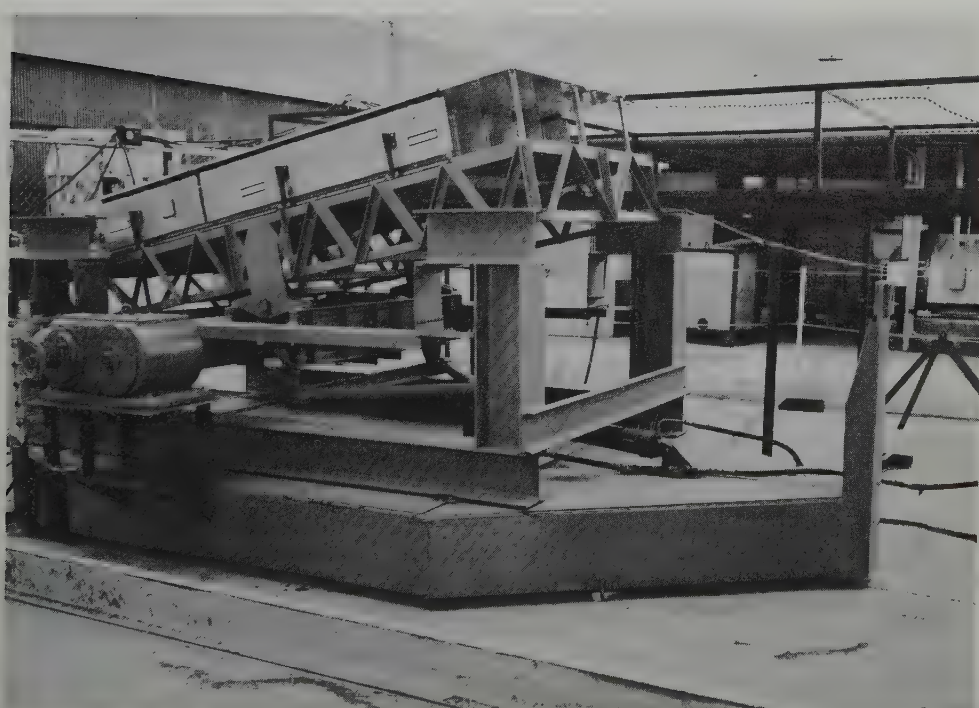

Fig. 20

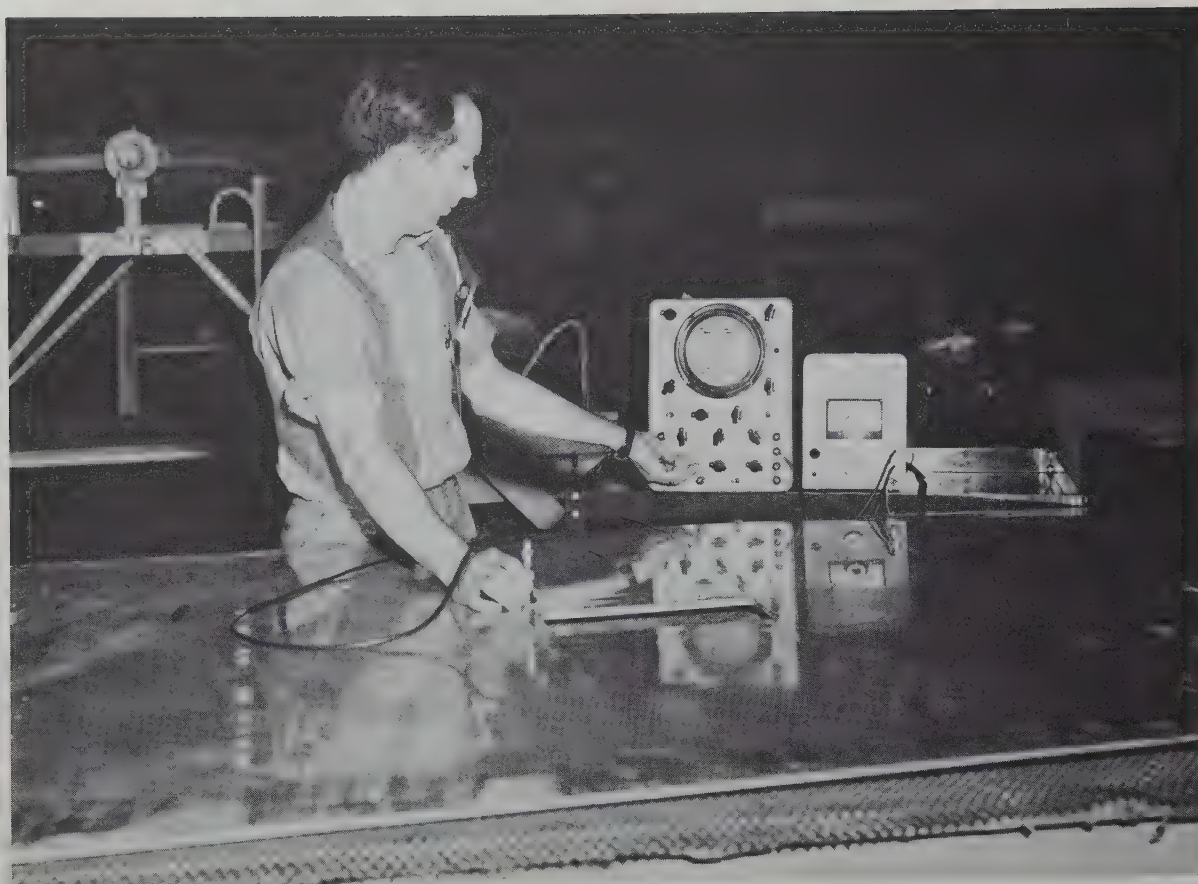

Fig. 21

inertial loading due to the movement of the fuel. The effect of vibration is also determined and this is also a life endurance test.

It is of little use to develop new types of structures unless simultaneously with their development the necessary tools for controlling the quality of the structure are developed. Very early in the program, Convair began looking for a satisfactory method of evaluating the soundness of an adhesive bond, both metal-to-metal and metal-to-core. Several ideas were tried. One particular idea obtained from Stanford Research Institute, from work done under an Air Force contract, proved most successful. This idea was taken and developed, and it materialized as a suitable production testing device. Figure 21 shows an inspector using this device. It is an ultrasonic impedance tester which consists of a power source for deriving a piezoelectrical crystal at one of its natural frequencies and a suitable detector for measuring impedance changes. The piezoelectrical crystal is coupled to the surface of the specimen being tested with oil. The detection circuit shows any variance of impedance from a standard panel.

The most difficult task confronting the engineer on this project is interpretation of data presented by the instrument. Finally, it is found that there is no problem if the instrument is used as a comparator and calibrated with standard panels having known defects. Figure 22 shows a typical signal indicating a complete void on a sandwich panel. If it were a good bond, the display would be a very narrow wavy line on the center of the oscilloscope. The display changes gradually into the shape shown in the illustration as the bond deteriorates and approaches that of a void. This device is only one of many quality control procedures used in manufacturing the sandwich panel.

Figure 23 shows the slugs of a large wing panel. Some of the wing panels have as much as 90 square feet per side. A wing panel being laid up is shown in Fig. 24. The core has already been inserted between the slug frames. Note the white gloves. It is necessary that surgical cleanliness be maintained throughout portions of this work.

Bonding presses are rather large. Figure 25 shows a bonding press which is closed. The panel being bonded has been placed between the steam-heated platens. The pressure applied to the panel is 150 pounds per square inch; the temperature is 350°F; and the time is 2 hours. Close tolerances must be held on all parts and the platen.

In order to get an idea of the extent of bonded sandwich panel, metal-to-metal bonding, and brazed sandwich panel, a breakdown of their

use is shown in Fig. 26. From this it is easy to see why the B-58 is sometimes referred to as the completely bonded airplane.

Prior to the flight of the first airplane, the critical sections are proof-tested. Figure 27 shows a typical proof test of the tail section of the B-58. During proof tests, loads are applied to 100 per cent of the design limit.

No doubt, all of you saw pictures in the press of the static test B-58 being carried by a B-36 to Wright Field for the final structural tests of the complete airplane. The airplane as it looked after being transported to Wright Field is shown in Fig. 28. The tail, control surfaces, nacelles, and landing gear were transported separately and assembled on the airplane at Wright Field. The airplane is being tested under specified load and environment conditions to failure.

As a result of all the testing that has gone on in the development of the structure for the B-58, we arrive at the final aircraft shown in Fig. 29. To date, flight tests of fourteen months indicate that as far as the structure is concerned, the B-58 was tactical the day it rolled off the final assembly line. It is hoped, for the sake of our country's economy and security, that the equipment manufacturers will soon have their development programs organized to achieve the same goal.

Fig. 22

Fig. 23

Fig. 24

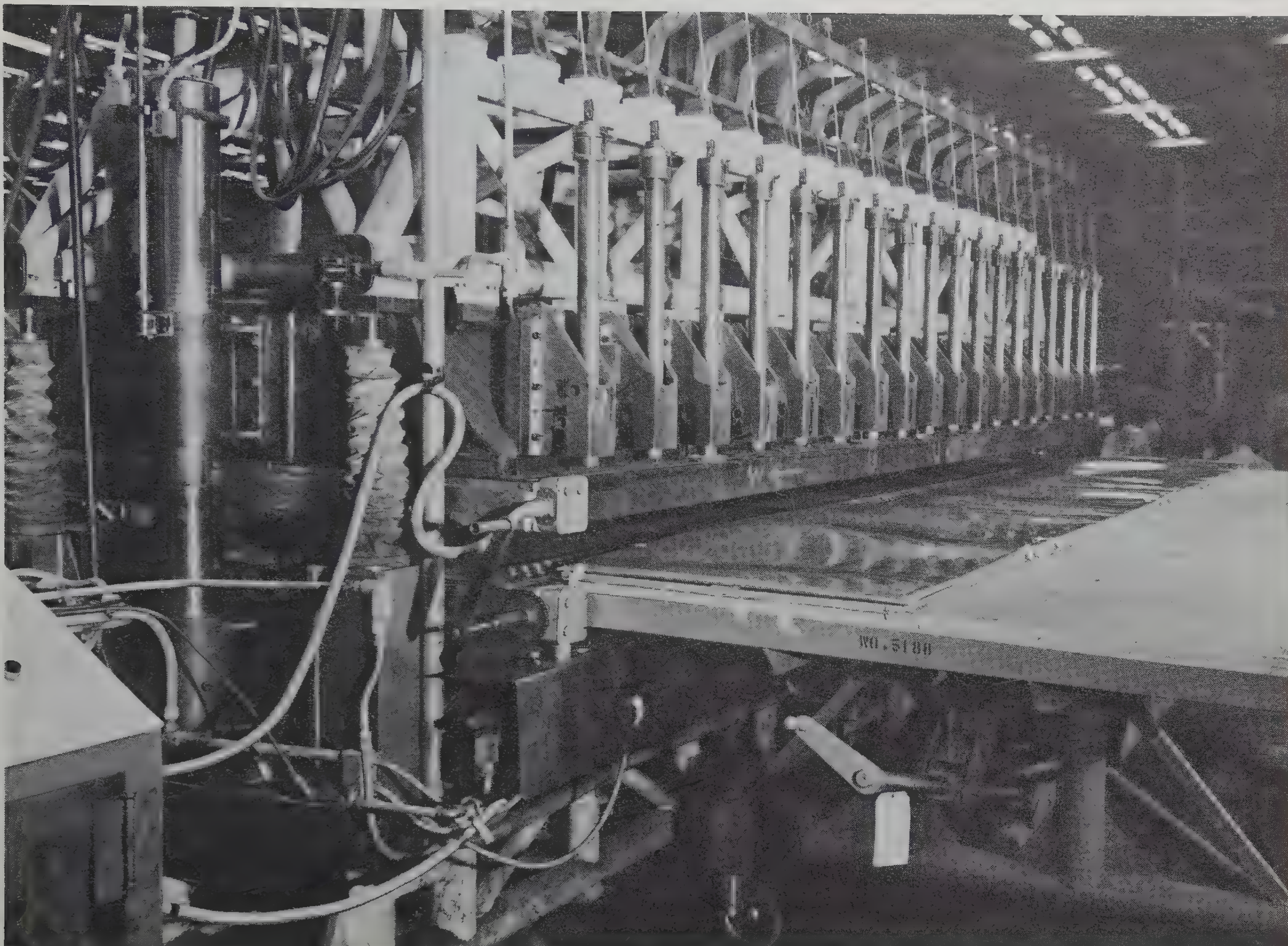

Fig. 25

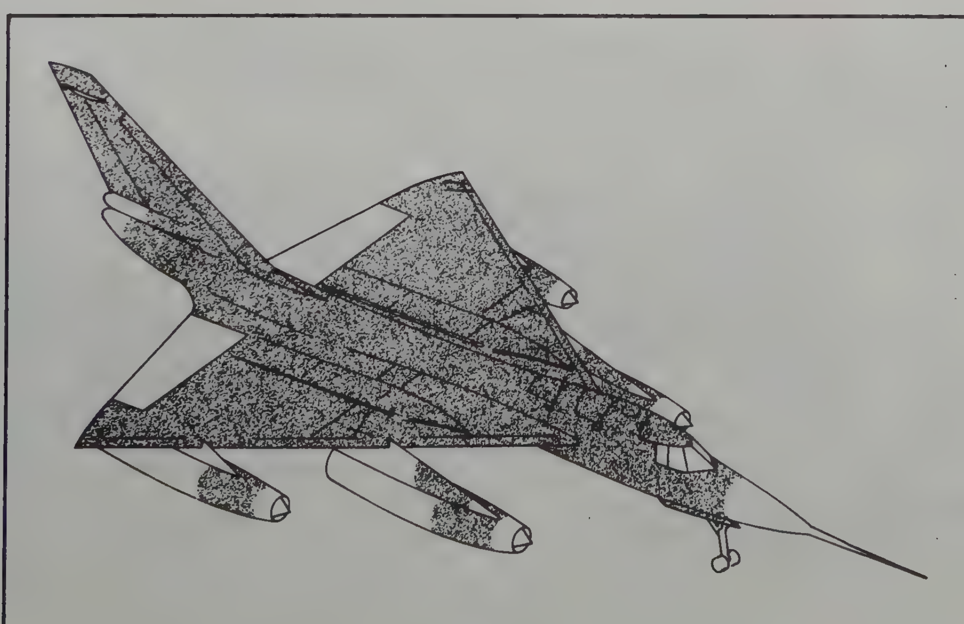

Fig. 26

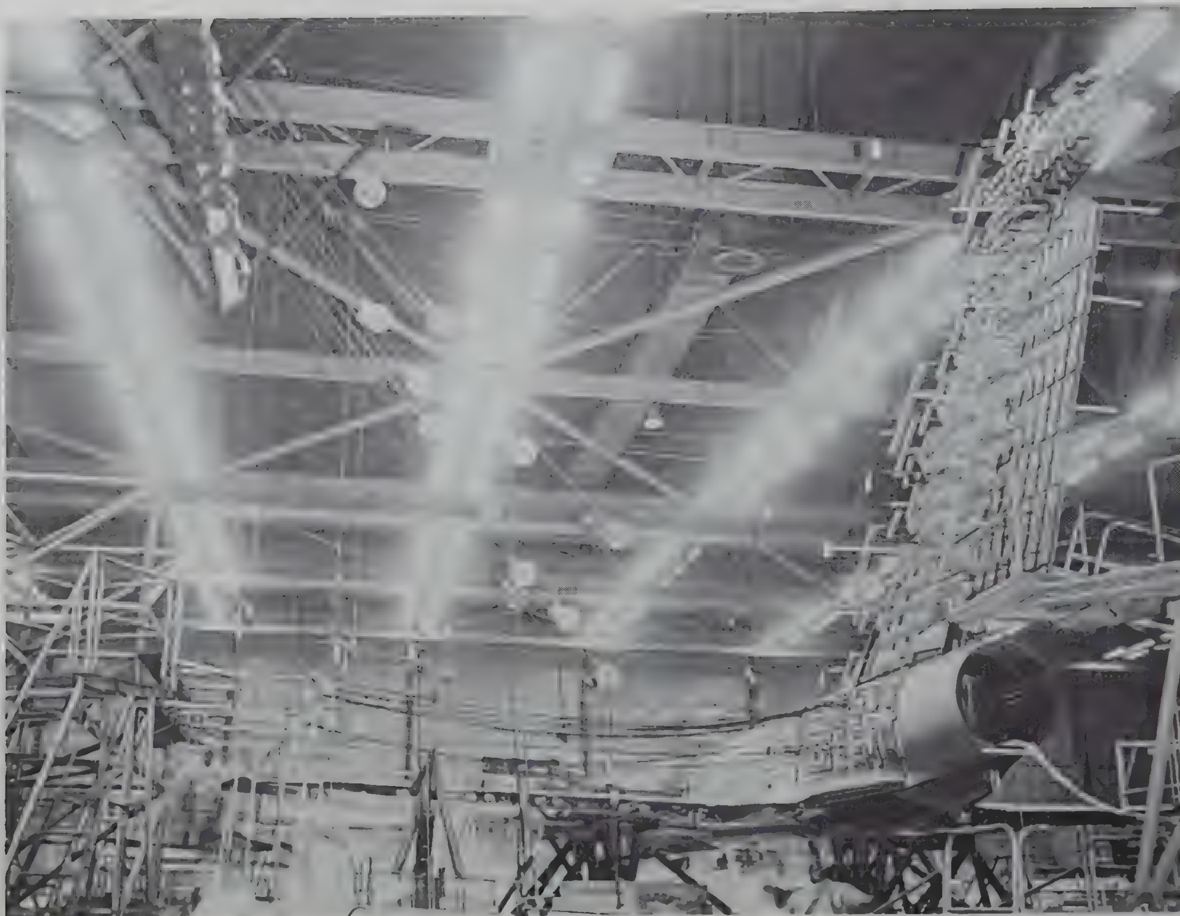

Fig. 27

Fig. 28

Fig. 29

SYSTEM ASPECTS

M. M. Tall
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Radio Corporation of America
Moorestown, New Jersey

An effective reliability program is concerned with two major areas of effort. These might be termed reliability assurance and reliability improvement. The assurance area is concerned with the steps one takes prior to "release;" the improvement area, with revealing and correcting reliability deficiencies subsequent to "release." As a dividing line the "release point" depends upon the activity considered. The dividing line selected is not pertinent to our discussion, nor is the fact that both areas may be carried on concurrently. What is important is the recognition that the assurance area represents the most economical effort in a reliability program and is worthy of renewed emphasis.

This discussion is concerned with an aspect of our reliability assurance program which has become an important management tool in directing reliability effort in an effective and economical manner. We call this effort the system effectiveness approach to reliability. In this approach we are concerned with the end result of reliability or lack of reliability; we are concerned with the effect of a failure on over-all system performance.

When we are dealing with a large weapon system which may be a multifunction and multichannel system, the normal measures of reliability lose their meaning. The normal measures, such as mean-time-between-failures, failure rate, and probability of failure-free operation, are primarily concerned with failure frequency. An additional dimension, such as failure severity, must be added.

Failure severity is a measure of the effect of a failure on system performance, and most importantly, the duration of this effect, i.e., down-time. Theory tells us we cannot reduce the probability of failure to zero. Thus it behooves us not only to reduce this probability to as low a value as possible but also to concern ourselves with the types of failure we can expect, the effect on system capability, and the time to detect, isolate, and correct the failure.

Since these factors are controllable to a large extent in design, their consideration becomes an integral part of our reliability assurance program. In addition, large weapon systems are generally custom-built rather than mass-produced. When relatively few systems are being constructed, we cannot set aside several for rigorous test, nor can we depend heavily on adequate field experience becoming available early in the production cycle. As a result, we must depend to a greater degree on our assurance techniques in order to achieve the desired degree of reliability.

As an illustration of the system effectiveness approach to achieving reliability, let's assume a simple missile fire-control system. The basic elements of this system are a radar, computer, and launcher. In operation the radar will be employed 100 per cent of the time; the computer, 50 per cent of the time; and the launcher, 25 per cent of the time. The best system plan has been selected in terms of system capacity and efficiency.* For purposes of illustration, a 4-2-1 system has been selected, as shown in Fig. 1 (that is, four radars, two computers, and one launcher). Thus, both computer and launcher idle time are reduced, and the capacity of the system has been multiplied four-fold.

A contractor's experience, particularly his documented experience, plays an important role from this point on. The technique requires that certain estimates or predictions be made. These estimates are based on contractor experience with his own designs as opposed to the generalized experience of all contractors' equipment. Of course some estimates may be gross in nature. This is an indication of how well prior experience has been documented. The further along a development progresses, the more sophisticated are the prediction techniques that may be employed. However, the value of the system effectiveness approach in the earliest development phases overrides the effect of gross estimates.

In our example we are given three basic functional types of equipment -- radar, computer, and launcher. Based on our prior experience and on the current state of the art, we can estimate the mean-time-between-failures and the mean down-time that we can achieve. At this point in the development, we are only concerned with the order of magnitude of the number of parts involved. Our reliability estimate for each equipment is initially based on what may be called the contractor's standard level of excellence.

Let me digress a moment and discuss the contractor's standard level of excellence. The cost of development of an equipment has been considered as increasing, some say exponentially, as a function of reliability achievement. It is not generally recognized that there is an area of reliability achievement where an applied reliability effort actually reduces development costs. This reduction may be attributed to the introduction of a design control function which reduces the number of repetitive errors in design, exerts a standardizing influence on part selection, and so on. In a sense, the engineering operation is made more

*Tall, M. M., and Sherman, S. M.: "Reliable System Design." Presented at the Second RETMA Symposium on Applied Reliability, Syracuse, New York, June 10 and 11, 1957.

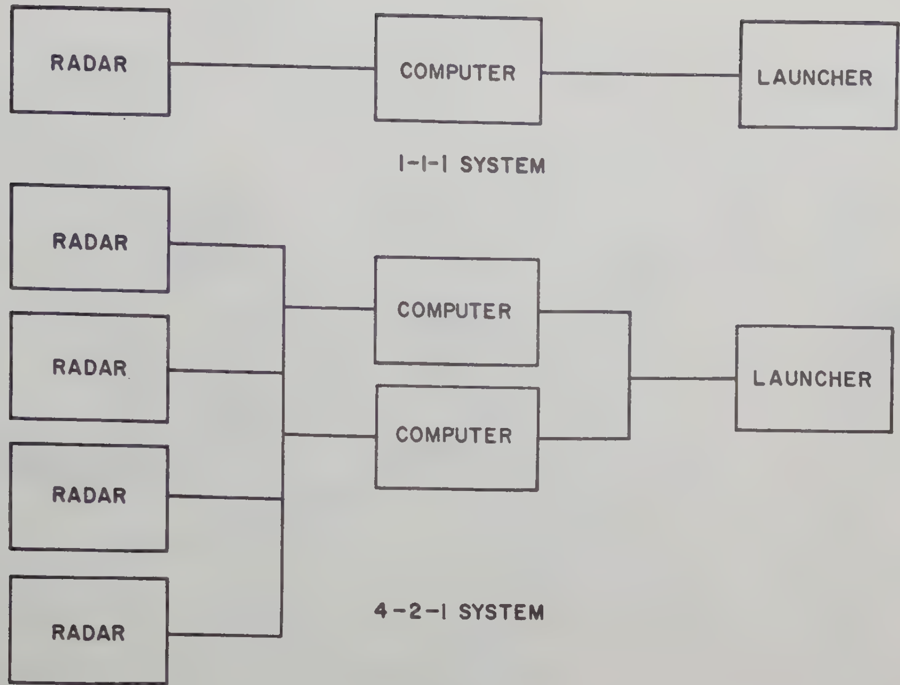

Fig. 1

efficient by the injection of documented reliability experience.

In Fig. 2 contractor development costs are shown qualitatively as a function of reliability. The minimum point which results from normal reliability controls represents the contractor's standard. This is the level a contractor seeks to achieve in the absence of specific quantitative reliability requirements. I do not intend to infer that this level may not be more than adequate for the equipment function. It does point out that our present procurement procedures which are based on price and delivery compel a contractor to build at this level.

For comparison purposes, the service support and over-all costs are shown. The service standard represents the minimum cost if a few systems are constructed, and moves to the right as the number produced increases. As has been said many times in the past, it behooves the services to pay higher initial development costs to achieve better reliability.

The service standard may be considered to be the specified level of reliability in the absence of rigorous reliability requirements. In regard to contractor development costs, it should be pointed out that the minimum point varies both vertically and horizontally, depending on the type of equipment involved and a contractor's experience with that equipment. In our estimate for each of the equipment types in our system, we take the contractor standard as a starting point.

With an estimate for each type of equipment in our system, we must define what we mean by system effectiveness for our particular system. In each case system effectiveness should be a measure of the output function of the system in its application. In our example we are concerned with a missile fire-control system. The output function is to guide a missile to a target. In addition it shall perform this function at some determined rate, that is, with a given system capacity or firepower. A good measure for this system might be relative firepower, the ratio of the actual or predicted firepower to the firepower that would result with 100 per cent reliability. Since we are concerned only with the fire-control system, we assume a missile reliability of 100 per cent.

If the missile is included in the system, a useful measure may be relative kill probability or kill probability, depending on one's point of view. In the first instance, we separate the inherent accuracy of the system from its reliability by accepting the fact that a 100 per cent reliable system has a kill probability of less than one. In this case the measure is the actual or predicted kills to the probable number of kills with 100 per cent reliability. On the other hand, we can assume that a 100 per cent reliable system has a kill probability of one, and the measure, kill probability, then includes both the factors of system reliability and accuracy.

It should be mentioned that this concept of measuring output in its application may be applied to subsystems, chassis, and even parts. We are all familiar with applications that can accept a part variation of 50 per cent or more and other applications where a part variation of 10 per cent or less would be considered a failure. The measure should reflect the real application requirement rather than an arbitrary one.

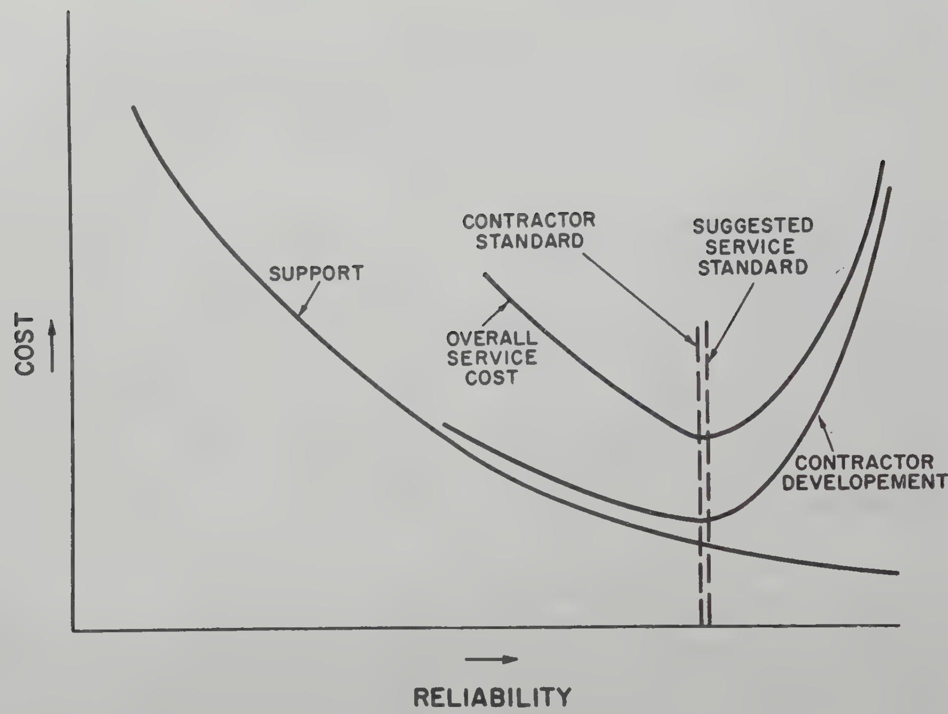

Fig. 2

With a definition of system effectiveness as relative firepower for our system, let us employ some illustrative numbers for the determination. Assume that the contractor standard for the radar yields a mean-time-between-failure which we will call T of 57 hours, and a mean down-time which we will call D of 3 hours. The computer has a T of 98 hours and a D of 2 hours; the launcher has a T of 990 hours and a D of 10 hours. Since our system should have an operational capability of 24 hours per day, we are concerned with the availability of each equipment or the probability that the equipment will be available at any given instant. Availability may be expressed as $A = T/T+D$ the mean-operating-time-between-failures divided by the sum of the mean-operating-time-between-failures and the mean down-time. Table I shows the availability for the various equipments.

Our particular system, a 4-2-1 system, will have a capacity or firepower of 4 for each cycle of operation. If this represents the firepower with 100 per cent reliability, failures will reduce the firepower to 3, 2, 1, or 0 depending upon the severity of the failures. In our system model, only integral values are possible. Our determination of relative firepower requires that we compute for what fraction of time each level of firepower exists and their wieghted average. Table II indicates the process we employ. The first column shows all combinations of operable and inoperable equipments. Thus, 4-2-1 means all the equipments are operable. The first number has five possible values (4, 3, 2, 1, and 0); the second has three (2, 1, and 0); and the third has two (1 and 0). Therefore, there are 30 possible combinations. However, it is not necessary to list them separately, since those with zero firepower can be conveniently grouped together.

The firepower for this simple system may be obtained by examining the system configuration and noting which unit is limiting for each combination. The formulas represent, in terms of unit availabilities, the fraction of the time that each combination will exist. It is helpful to think of the availabilities as probabilities. Note that on a 24-hour-per-day schedule, the system will be fully operable 77.4 per cent of the time and completely inoperable only 1 per cent of the time. This, of course, is due to the redundancy in the system.

We call the type of redundancy employed functional redundancy, as opposed to spare redundancy. Functional redundancy is equipment duplication which contributes to the system capacity as well

TABLE I

Equipment Availability

$$A = \frac{T}{T + D}$$

Radar:	$T = 57,\ D = 3$	$A_R = \dfrac{57}{57 + 3}$	$= .95$
Computer:	$T = 98,\ D = 2$	$A_C = \dfrac{98}{98 + 2}$	$= .98$
Launcher:	$T = 990,\ D = 10$	$A_L = \dfrac{990}{990 + 10}$	$= .99$

TABLE II

Relative Firepower Computations

Combination	Firepower	Formula	Availability
4-2-1	4	$A_R^4 A_C^2 A_L$	.774
3-2-1	3	$4A_R^3(1-A_R)A_C^2A_L$	.163
2-2-1	2	$6A_R^2(1-A_R)^2A_C^2A_L$	.013
1-2-1	1	$4A_R(1-A_R)^3A_C^2A_L$	.000
0-2-1	0	$(1-A_R)^4A_C^2A_L$	.000
4-1-1	2	$A_R^4 2A_C(1-A_C)A_L$	.032
3-1-1	2	$4A_R^3(1-A_R)2A_C(1-A_C)A_L$	.007
2-1-1	2	$6A_R^2(1-A_R)^2 2A_C(1-A_C)A_L$	.001
1-1-1	1	$4A_R(1-A_R)^3 2A_C(1-A_C)A_L$	.000
0-1-1	0	$(1-A_R)^4 2A_C(1-A_C)A_L$	.000
M-0-1 (5 cases: M=4,3,2,1,0)	0	$(1-A_C)^2A_L$	.000
M-N-0 (15 cases: M=4,3,2,1,0 and N=2,1,0)	0	$1-A_L$	.010
			1.000

as to reliability. Spare redundancy is duplication which does not increase system capacity but is intended only to improve reliability. The economy of functional redundancy achieved by multiplexing or time-sharing equipments leads us to seek this type of solution for improved reliability wherever possible.

Since several combinations yield the same firepower, we group them together in Table III. The average firepower is obtained by multiplying each possible firepower condition by its probable occurrence and summing the products as shown. Relative firepower is the ratio in per cent of the average firepower to the firepower that would be obtained with 100 per cent reliability, 4 in this case.

A relative firepower of 92 per cent is the value we would attempt to deliver in the absence of a specific quantitative reliability requirement. This firepower results from designing equipment to the contractor's standard level of excellence. If this value is satisfactory or meets a specified reliability requirement, our task becomes one of monitoring to insure the maintenance of the contractor's standard. In the event a reliability requirement beyond this value is specified, our next step is to determine the most economical solution for the requirement.

This step might be termed the "system sensitivity" phase of the analysis. This phase simply involves the determination of the effect on relative firepower of equal proportional improvements in the availability of each equipment type. Table IV shows the results of substituting improved values of A_R, A_C, and A_L one at a time. An incremental improvement of 1 per cent was applied to each of the availabilities. The important part of this table is the value of the ratio of the per cent improvement in average firepower to the per cent improvement in availability. The results are not particularly surprising in this simple system, although they may prove to be so in some of our more complex systems.

TABLE III

Relative Firepower

Firepower	Probability	FP X P
4	.774	3.096
3	.163	.489
2	.053	.106
1	.000	.000
0	.010	.000
	1.000	3.691

Average firepower: 3.691
Relative firepower: 92%

TABLE IV

System Sensitivity

Incremental improvement: 1%

	Orig.	Improvement 1	Improvement 2	Improvement 3
A_R-	.95	.950	.959*	.950
A_C-	.98	.980	.980	.989*
A_L-	.99	.999*	.990	.990
Average firepower	3.691	3.725	3.723	3.722
Relative firepower (%)	92	93	93	93
$\frac{\text{Av. firepower improvement}}{\text{Availability improvement}}$	-	1.00	0.87	0.84

*Improved value of availability.

The next step in the analysis involves estimating the cost of achieving these improvements in availability. For the sake of simplicity, let us assume a unit cost for the radar, 1.5 times the unit cost for the computer and 2 times the unit cost for the launcher. It should be recognized that cost estimates for the first incremental improvement do not necessarily hold for a second or larger incremental improvement, although their relative order may remain the same.

In Table V we see that the radar with the greatest room for improvement yields an improvement of 0.87 per unit cost, whereas the launcher which affects the average firepower most directly yields an improvement of only 0.50 per unit cost. Several additional increments can be estimated in a like manner. The combination yielding the desired level of reliability at minimum cost is selected.

TABLE V

Improvement Costs

	FP Impr. / Avail. Impr.	Cost of Impr.	Impr./ Unit Cost
Radar	0.87	1	0.87
Computer	0.84	1.5	0.56
Launcher	1.00	2	0.50

Inherent in these cost estimates is the system's application. Remember that availability is equal to the mean-operating-time-between-failures, T, divided by the sum of the mean-operating-time-between-failures and the mean down-time, D. An improvement in availability may be achieved by increasing T, decreasing D, or both. In a system having a 24 hour capability requirement, we can tolerate an increase in the failure rate (decrease in T) if we can substantially reduce the mean down-time. On the other hand, some applications may require a high probability of failure-free operation (increase in T) for some period of time regardless of the down-time which may occur as a result of failure. This situation may occur in a device which we do not intend to repair. Other situations may be compromises where we may desire to perform maintenance at convenient intervals.

Since the decisions resulting from this analysis were based on engineering judgements and estimates, some of which may be gross, the analysis is kept current as work progresses. It continues to serve in guiding the system development toward the achievement of the required reliability at the minimum investment.

RELIABLE SYSTEM DESIGN BY PART ENGINEERING

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This paper will concern itself with the organization and activity of a component application engineering organization and the part it plays in the development of electronic systems with particular emphasis on those aspects which influence the reliability of the system.

The reliability of electronic systems is a function of, among other things, certain characteristics of the component parts and the manner and extent to which those characteristics are stressed in the system application. It is therefore imperative that those designing electronic systems have readily available to them information concerning the characteristics of component parts including the correlation between application stress and failure rate. The determination of these factors is a task for experts in the field and not for standards engineers or abstractors of catalogues. In addition, it is true that a high percentage of component development and modification is financed by electronic system development funds. The establishment of new component requirements and the transmittal of those requirements to those doing component development should be left neither to standards engineers nor to the equipment designers, since each is a specialist in a different field. For these and other reasons, it is our opinion that an electronic equipment development organization can no more do without a component engineering capability than an equipment manufacturer can do without a quality control organization. The size and nature of this component engineering capability is, of course, a function of the size, organization, and nature of work of the particular equipment development activity. This component engineering capability may vary from one senior engineer encompassing all electronic parts to a large comprehensive organization such as exists at Hughes Aircraft Company, having a number of senior specialists in each component field, such as transformers, resistors, capacitors, relays, semiconductors, etc.

Regardless of the size of the component engineering activity or the organizational context in which it finds itself, to be really successful, there are certain requirements which must be satisfied. Without these, a highly successful program is not possible.

1. The personnel must be of high professional calibre. Without this, what follows cannot be done, and program is doomed to failure. Design engineers tend to express their requirements in terms of circuit parameters, whereas the components industry in general tends to express component capabilities in component terms. The component application engineer must have the ability to communicate with both the design engineers and with people in the component industry in their own respective languages. Experienced personnel of this sort are exceedingly difficult to come by and must generally be trained on the job.

2. The organizational structure must be such that the components engineers are able to work freely and closely with the design engineers at the working level. Certain equipment manufacturers have made the mistake of assembling a group of competent experts at a high staff level, which makes a close relationship with the working-level design engineers exceedingly difficult.

3. The components engineering organization must have the responsibility of preparing preferred parts lists and application criteria, and must be permitted to exercise control over components application. Obviously, since the components organization has no direct design responsibility, it cannot have final design authority. If it is to be overruled, however, such overruling should come from the project management rather than the design engineering level.

4. The components organization must have management support. Top management support is particularly important in the case of any service organization such as this. Management must see to it that the organization is properly equipped with personnel, laboratory facilities, and funds. In addition, it must be clearly extablished in their charter of operations that they are the contact point in engineering on all matters pertaining to component parts. This implies that field and factory problems on component parts are referred to this organization.

5. The authority must rest with the components engineering organization to approve component sources of supply for the company. It should not be left to the discretion of purchasing or any other organization to assure itself that one vendor's product is the equivalent of another. This is an engineering function and must be done by the component engineering organization. In addition to the other advantages accruing from a procedure of this sort, it gives the component engineering organization a large lever in operating with component vendors. A component supplier is much more likely to cooperate in the development of a component with an organization if that organization is also the one which has the authority to approve or disapprove the sources of supply.

6. The component organization must, in addition to the above, have responsibility for the whole component engineering function, including the preparation of specifications and standards and the evaluation of components. Obviously, only the design engineers can determine component characteristic requirements, but the selection of the exact part and the source of supply should rest with the component engineering organization.

7. A portion of the effort of the component engineering activity should operate on a continuous basis and not be tied to specific projects or problems. Only in this way may advanced work proceed and may the design activity be assured of proper components being available when required.

One may speak of a reliability engineering program only during the development phase of the system. Once a design is firm and released to production, one is no longer working on reliability but on unreliability. The problem is no longer one of designing reliability into the system but of removing unreliability from it. The function of the component engineering activity during the development time of a system may be divided into two aspects, that involving the work with the design engineers and that involving vendors. The design engineers need to be furnished with lists of preferred and proven parts, application notes, and a consulting engineering service. Component application engineers should sit on design review boards and, in general, work closely with the design engineer. On the other hand, the component engineers need to begin communicating with potential sources of supply. Requirements for new components need to be transmitted to the vendors by means of definitive specifications. It is our feeling that the importance of specifications has been overemphasized in that the concept is frequently overlooked, that during the development program they serve merely as means of communication. The components manufacturer needs to be told clearly and completely the requirements for new components, preferably in his own language. The choice of a proper supplier is all-important, since it is our feeling that a supplier who lacks either competence or integrity cannot be depended upon to furnish reliable components no matter how stringent the specification, or how rigorous the quality control procedures may be. Samples of the components should be obtained and evaluation tests conducted. Again, we feel that the importance of qualification tests has in the past been overemphasized. The levels of reliability currently required are such that very little useful information may be gained in that regard by the running of a few tests on a comparatively small number of samples. Rather, it is felt that tests should be conducted which will give a component expert information pertaining to the adequacy of the vendor's design, and that approval or disapproval of the component and of the supplier should be based upon a total consideration of the component and the vendor's capability, rather than go, no-go tests of a qualification nature.

A different sort of task is that associated with removing unreliability from an existing system. The work here starts with analyzing failures during design environmental tests and continues on a larger scale during the production of the system. System reliability testing as a normal production test, usually on a sampling basis, has been underway at Hughes Aircraft Company for a number of years. The trend of mean time to failure in these tests is watched closely, particularly with regard to those component failures chiefly responsible for determining the mean time to failure. After a system is in the field, rapid accurate and complete failure feedback information is essential.

Once major unreliability problems are isolated, there is no substitute for the prompt return of failed components together with the components' histories. The component part should then be carefully analyzed in the light of its history and application. This may be done by the component engineer or preferably, where possible, the part, its history, and application information should be returned to the vendor. At the Hughes Aircraft Company such a feedback program has been underway for several years with very satisfactory results.

It is my opinion, based on examination of unreliability problems encountered in many different types of equipment, that too much has been said about the statistics of the problems, about the interpretation of the statistics, and not enough about the underlying causes of the problems. In particular I make reference to the fact that the whole field of reliability has become shrouded with an aura of probabilities, statistics, mountains of data, and theory. Much of this is necessary and proper. Some of it, however, has tended to hide the fact that a very high percentage of the reliability problems with us today are simply the result of poor engineering, and that a careful examination of a relatively small sample of failed components will reveal poor component design or fabrication techniques, or gross misapplication. If we are requiring reliability levels ten times higher than those presently obtained, then new techniques are required, and very subtle characteristics of components and their application become all-important. I sincerely believe that an honest appraisal of most present reliability problems will result in the conclusion that there have been design and manufacturing errors which would have been easily correctable if detected during the time the equipment was being designed or fabricated.

The proper use of a comparatively small number of component and reliability engineers at this early stage will have a much greater effect on the ultimate reliability of the system than any other means presently at our disposal.

THE CHALLENGE OF RELIABILITY TO MANAGEMENT

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The period since World War II has presented many challenges to industrial management. The skill, imagination, and determination used in facing these challenges has made the difference between success and failure.

In the last few years, product reliability has climbed to a prominent position among the issues requiring management attention. It is related to other vital issues characteristic of these times. For example: technical progress has been accelerating; there is great pressure to reduce the time required for new developments; the upward spiral of costs causes problems. It is management's job to fit product reliability into its proper place, and to determine what program of action will bring results.

But certain points are indisputable. We are bound by our formula of national defense to work on the basis that there can be no excuse for product failure. Indeed, we cannot expect to have the time to make an excuse for failure. The weapons and weapon systems we employ must work precisely as they are intended to work. They must do the job of keeping an enemy off our heads, and they must do it on an instant's notice, thoroughly and efficiently and with no margin for error. One error, in the age of the H-bomb, means certain disaster. We must make sure that such an error cannot possibly be permitted by the failure of some electronic or mechanical device, small or large, simple or complex.

Another consideration is how we look to the rest of the world -- call this prestige, face, reputation, or what you will. Second place at the diplomatic bargaining table is no better than second place in nuclear warfare. As a nation, we must retain our proper position as the leader of the nations that do things. Our accomplishments must speak for themselves -- not on paper, not in conversation, not in the rosy plans for the future. We must be known as the nation whose weapons are to be respected, so that no one will dare to try us out for size.

This does not mean that we should rush to the launching pads before we are ready. But whatever we do undertake, say the firing of an ICBM or the shooting down of a defenseless drone in routine practice, must come off as scheduled. That is not an original thought, but it is one we must keep in mind as we design, develop, and produce.

Every little movement will have to go according to plan. And that means reliability with a great big "R." This brings us back to the problem of industrial management. These technical, schedule, and cost issues have many interactions with the question of reliability. There is ample evidence that a product will be most dependable when it has been thoroughly de-bugged, when design has been stabilized, and when a steady flow of production is coming from hard tooling.

The increasing pace of technical advancement upsets this approach. A parts manufacturer whose design is static for as much as three years will find his markets disappearing. A missile that waits for the completion of every conceivable test before entering production will be obsolete before it is available. Management, both industrial and military, has had to balance the risk of coming too late against the risk of trouble with the product.

The rapid pace of development has other effects that are particularly noticeable in military electronics. It has turned out that there are an increasing number of military tasks that can be accomplished only through the use of electronic equipment. While there have been strenuous efforts to simplify designs, any benefits are offset by the increasing list of jobs to be done. One result of this trend to complex equipment has been the extraordinary demand for uniformity and dependability on the multitude of circuit parts. In addition, the new tasks have thrust electronics into unfriendly environments. Designers face an ascending scale of stresses to the point where the raw materials themselves lack the strength to survive.

This reach for technical advancement has had a serious effect on equipment costs. We must add the steady upward trend of the cost of labor and materials. The manager of commercial enterprise must worry about shrinking markets, and in the military field the burden on government budgets is well-known.

An attempt to achieve reliability without regard for cost is as impractical as disregarding development time schedules. For example, the effort to increase reliability has led to added tests on system and major assemblies and on the thousands of detail parts. Any attempt to develop this approach to its logical extreme would soon consume all of a manufacturer's floor space, equipment, and operating man-hours.

So the question of equipment reliability must compete for management's attention against the issues of schedule, performance, and cost. The competition has been unequal in one respect; that is, the other issues have quantitative goals, and success in meeting them can be measured. New equipment must be delivered by a certain date, and its range, gain, or sensitivity must achieve measurable advances. Failure to meet these goals threatens the company's business future, and failure to keep costs within the funds available is equally damaging.

Reliability, on the other hand, has not had a quantitative goal. It has not been measurable until equipment was produced and in use. That managements have concentrated their attention on the requirements that could be measured should not be surprising. This weakness has been recognized. The Department of Defense, the military services, and the more enterprising industrial managements have been tackling the question. It is not too difficult to decide that, under a given set of circumstances, equipment should work 90 per cent or 99 per cent of the time. But this step raises more questions than it settles.

When and how is compliance to be demonstrated? Can a prediction be made from the drawing board? It has been shown that improved design techniques can achieve a ten-to-one reduction in failure frequency between one model of equipment and the next. Can a high order of reliability be demonstrated with reasonable accuracy by tests on a small quantity of laboratory models? Will tests run in the factory before delivery correlate with results in service use?

We have only the beginnings of answers to these questions. A prudent management will take a hard look at the degree of business risk involved in reliability specifications. There is the very real danger that too much money and manpower will be tied up in demonstrations, to the detriment of the real job of improving the equipment. With experience, it should be possible to include reliability among the other factors that management has learned to measure and control.

That quality and dependable performance must be built into a product is a frequently repeated truism. It is equally true that reliability is everybody's job from the janitor who cleans a work bench to the general manager who decides whether or not to invest in a new test facility. Something that is everybody's job is always in danger of being taken for granted; the wheel gets grease only when its squeaking cannot be ignored. It is a principle of modern management to set up agencies whose job is to assure that the company's objectives are being fulfilled. There is an increasing tendency to handle reliability in this manner.

If we are to achieve the decided advances that are necessary, the old ways of doing things will not always be good enough. New approaches are needed to design development, and more effective test methods are required. The process of uncovering the cause of failures and of incorpor rating improvements must be speeded up. The effort must reach across every activity of the company. There are undoubtedly many acceptable organizational approaches, but management needs a function that can help to establish policy, promote new approaches, and report major questions for action. The reliability job is not one that can be done by business management alone. A number of specific problems need joint action by the industry-military team. Some realistic thinking is essential on the trade-off between performance and reliability.

Electronics has been able to perform so many fascinating tricks that we have sometimes forgotten to count the cost of added features. There is no escaping the fact that each added "black box" inevitably adds opportunities for failure. We have also been forgetting to pay the piper on another score. We establish the need for a formidable new system, and then start looking around for the parts to put it together. It has been very difficult to get money for research leading to parts development until a definite equipment application is in sight. This is too late.

The systems designer must decide whether to use proven but less than adequate parts or to throw his hat at developments that are still on the horizon. Some unhappy results have come from following the latter course. No one company or project carries enough weight to move the parts-manufacturing industry toward the broad advances demanded by the tasks we are attempting. An expanded research program is needed, if we are to develop the bits and pieces for tomorrow's equipment.

In another area the equipment manufacturer is at the marcy of factors beyond his control. Data from service operations shows that the results achieved are many times more variable than can be accounted for by differences in the equipment itself. When the reasons are investiagted, we find that there are blocks in the spares supply line, that test equipment is not available to support maintenance operations, and that techniciams lack training and experience. It is industry's job to relieve this problem by reducing the need for excessive maintenance, and by making field check-out easier to handle.

But the human factor will not be eliminated tomorrow. This technical age requires an ever increasing body of skilled personnel. Education, industry, and the military must tackle the problem of increasing this essential resource.

Finally, no program to improve the dependability of equipment is going to get very far until we provide for the fact that reliability costs money. There is an initial investment that must be made before we realize the pay-off. A management is willing to buy an expensive new machine tool because it will soon pay for itself in reduced manufacturing cost. The same principle should apply to reliability. During the service life of equipment, the bill for spares, maintenance, retrofitted changes, and lost operating efficiency runs several times the original price. Unfortunately, the military services keep the money for this kind of expense in one pocket and the money for new equipment in another. Because of the drive to reduce current procurement costs, manufacturers have a hard time getting support for reliability improvement programs. We must recognize the opportunity that exists for substantial savings in the over-all cost of military equipment.

It seems to be characteristic of the electronics industry that things are seldom dull. New devices constantly upset the established concepts

of design, and whole new field open up for industrial and military applications. Reliability, or the lack of it, is just another measure of management's ability to take these changes in stride -- to handle the fast moving cycle of research, development, and manufacture without losing control over the factors that determine the inherent worth of the product.

UTILIZATION OF COMPONENT PART RELIABILITY INFORMATION IN CIRCUIT DESIGN

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Summary

Component part reliability testing programs of varying scope are in progress in many areas of the electronics industry today. These programs differ in magnitude, levels of environmental and electrical stress, and types of component parts tested, but properly designed programs have one aspect in common: They can result not only in reliability evaluation, but also in reliability improvement. This paper will discuss techniques for optimizing circuit reliability by application of component characteristic data obtained from reliability testing.

This reliability testing, if its value is to be maximized, should be conducted concurrently with the issuing of circuit design requirements and just after comparative evaluation testing has selected the most suitable component for an application.

Reliability testing of component parts yields data regarding the changes in electrical parameters, including changes of a catastrophic nature, as functions of environmental and load stresses and time. Reliability improvement results from minimizing these changes or their degrading effects on the output of the circuit in which the component parts are employed. This may be accomplished (1) by selection of the most suitable component parts, (2) reduction of stresses to the lowest practicable level, (3) circuit design to accept known electrical parameter drift rates for the required period of operating time of the equipment and (4) circuit design for compensation (Trade-off) of drifts of one component type for another.

Of these techniques, the first two are not usually wholly within the province of the circuit designer. Parts selection is subject to considerations of price, availability, size, and weight; it is normally the function of the components engineer, working not only with the circuit designer but with the project engineer and the purchasing department as well. Similarly, stress reduction is limited by the above considerations compounded with the factors of package design, availability and advisability of cooling, possibility of mechanical isolation, and the like.

Once parts have been selected and stress levels defined, however, it is the circuit designer's responsibility to effect optimum component parts utilization for reliable performance of the circuit. The designer must abandon the traditional approach involving "as-purchased" values and tolerances, and make maximum use of the output of reliability testing: Statistical information regarding the changes in electrical parameters during service life.

That the needed component performance information must come from reliability testing is obvious from a survey of available literature. Manufacturers' data sheets and catalogs yield no more than "typical" values of drift and survival under a few environmental or electrical stress conditions, and there is no way of extrapolating such limited data to the stress levels actually encountered, nor can drift distribution or range be determined. Similar limitations are inherent in conventional qualification test results, which are reduced further in usefulness by not being representative of the components actually purchased but rather of a carefully selected group.

As will be seen shortly, the circuit designer must be able to obtain, directly or by interpolation, component parameter drift characteristics under the stress conditions applicable to the specific equipment, and must know the distribution -- unit-to-unit variation -- of drift characteristics. Reliability test information of this type is becoming available gradually as the testing concept is implemented by various military agencies and contractors.

Let's look at some examples of the application of component performance data. Our first step will be to determine the probability of units to be used in production drifting outside specified circuit tolerance limits, when the units are subjected to service conditions. For ease of presentation and computation, let us assume that value and drift distributions are available in histogram form. Figure 1 shows the distribution of as-received values, and Figure 2, the characteristic distribution of parameter drift of the component type for the stress conditions and desired operating time as determined from previous reliability testing.

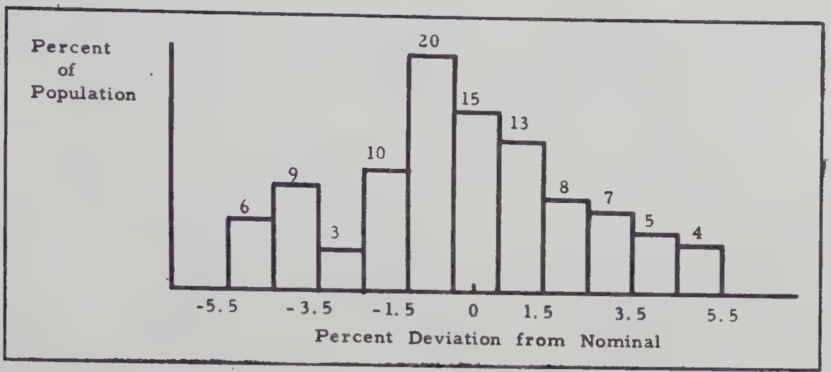


Fig. 1 - Distribution of as-received component values.

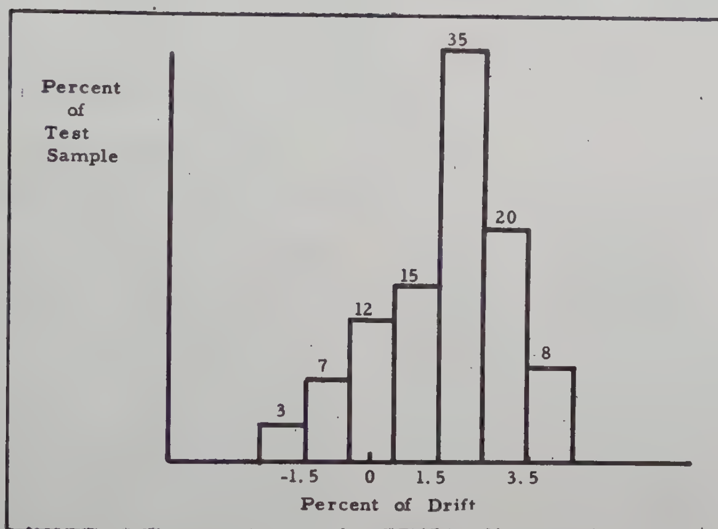


Fig. 2 - Drift characteristics for the required period of operation.

We now proceed to a step-by-step computation to determine the percentage of units which will drift outside circuit tolerance limits, say ±6% of nominal.

Initial value referred to nominal (1)	% of population in this range (2)	Drift causing failure (3)	% of population exceeding (3) (4)	% of population failing ((2) x (4)) (5)
		Lower Limit		
4. 5-5. 5	4. 0	-11. 0	0. 0	0. 00
3. 5-4. 5	5. 0	-10. 0	0. 0	0. 00
2. 5-3. 5	7. 0	- 3. 0	0. 0	0. 00
1. 5-2. 5	8. 0	- 8. 0	0. 0	0. 00
0. 5-1. 5	13. 0	- 7. 0	0. 0	0. 00
-0. 5-0. 5	15. 0	- 6. 0	0. 0	0. 00
-0. 5-1. 5	20. 0	- 5. 0	0. 0	0. 00
-1. 5-2. 5	10. 0	- 4. 0	0. 0	0. 00
-2. 5-3. 5	3. 0	- 3. 0	0. 0	0. 00
-3. 5-4. 5	9. 0	- 2. 0	3. 0	0. 27
-4. 5-5. 5	6. 0	- 1. 0	10. 0	0. 60
			Lower Total	0. 87

(cont.)

Initial value referred to nominal (1)	% of population in this range (2)	Drift causing failure (3)	% of population exceeding (4)	% of population failing ((2) x (4)) (5)
		Upper Limit		
4.5-5.5	4.0	1.0	78.0	3.12
3.5-4.5	5.0	2.0	63.0	3.15
2.5-3.5	7.0	3.0	28.0	1.96
1.5-2.5	8.0	4.0	8.0	0.64
0.5-1.5	13.0	5.0	0.0	0.00
-0.5-0.5	15.0	6.0	0.0	0.00
-0.5-1.5	20.0	7.0	0.0	0.00
-1.5-2.5	10.0	8.0	0.0	0.00
-2.5-3.5	3.0	9.0	0.0	0.00
-3.5-4.5	9.0	10.0	0.0	0.00
-4.5-5.5	6.0	11.0	0.0	0.00
			Upper Total	8.87
			Grand Total	9.74

Our computations tell us that our component failure rate due to drift will be 9.74, in addition to catastrophic failures. (Note that allowable drift is computed from the midpoint of the value interval, and that the entire drift containing the maximum allowable drift is counted toward failure contribution; these approximations neutralize each other within our limits of accuracy. Note also that, for more precise computation, drift percentages outside the range in the histogram could be estimated by drawing a frequency distribution curve to fit the histogram.)

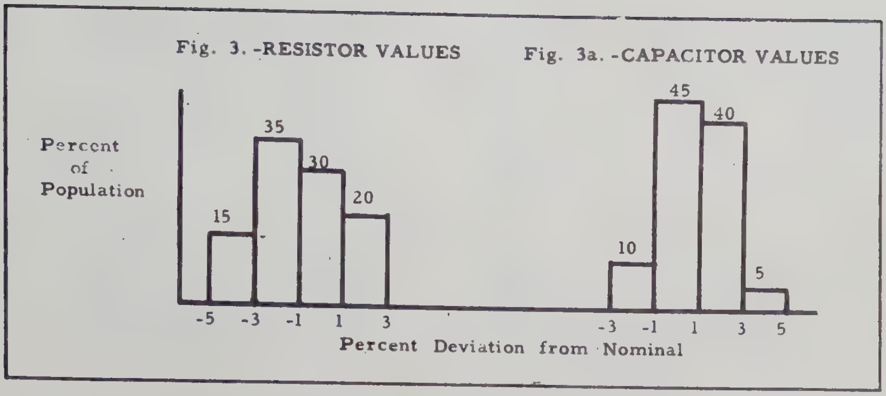
A component (drift) failure rate of 9.74% is likely to be intolerable in most applications. We can improve our situation in any or all of the following ways:

1. By increasing circuit tolerances
2. By reducing drift (as by stress reduction)
3. By tightening purchase tolerances or by tolerance reduction through selection from purchased components.

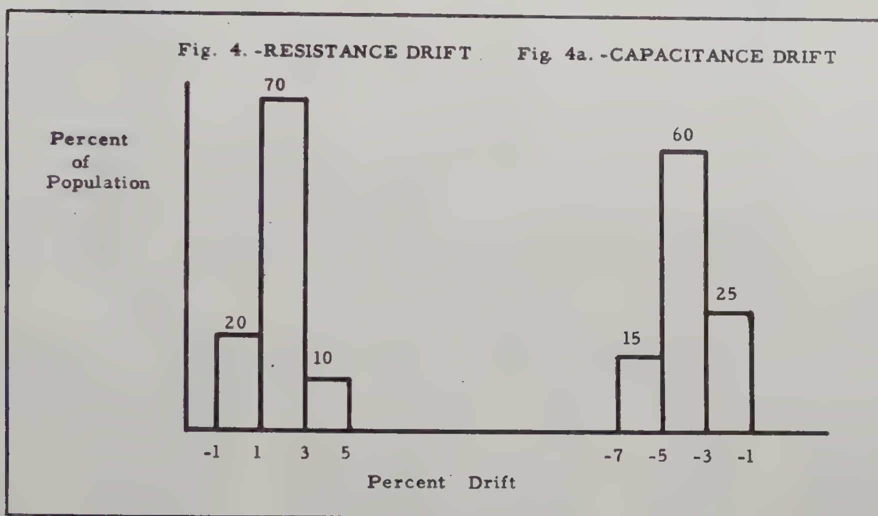
We assume, for the moment, that steps 1 and 2 are not possible under our application conditions. To determine the procedure to be followed in step 3, let's re-examine our table of computations. We find that all our failures are contributed by components whose as-received value falls more than 3.5% below nominal or 1.5% above nominal; drift failures could be virtually eliminated by prescribing tolerances of plus 1%, minus 3%. In the process of tolerance reduction, 39% of the original components would be screened out. To increase yield on future orders, it may be appropriate (depending on component type and purchase quantity) to revise the nominal value to obtain symmetrical tolerances. THE RELIABILITY IMPROVEMENT TECHNIQUE DEMONSTRATED IN THIS EXAMPLE IS APPLICABLE GENERALLY, WITH THE LIMITATION THAT DRIFT MUST BE RELATIVELY INDEPENDENT OF INITIAL VALUE.

In many cases, an additional reliability improvement may be realized by trade-off among component types. In the above example, initial tolerances may be decreased by 1% in the minus direction (to plus 1%, minus 2%) at the relatively insignificant cost of approximately 3% of yield. The circuit tolerance may then be tightened to plus 6%, minus 5% (of nominal). This tolerance reduction may be applied to increase the tolerance band on another component, with a consequent reduction in that component's drift failure rate.

Oftentimes, knowledge of drift characteristics (direction, magnitude, and distribution) may be utilized in the selection of components whose drift is such as to allow trade-off by compensation. Just as components of appropriate temperature coefficients are used in compensation for one another under the influence of temperature variations, drift -- which might appropriately be called a "time coefficient" -- can be employed in compensation for the aging effects of operating time. Again, let us illustrate by a simple example.



Figs. 3 and 3a - Initial distributions of resistor and capacitor values.



Figs. 4 and 4a - Drift characteristic distributions for resistor and capacitor values.

We assume that the circuit of interest is a simple R-C network whose time constant (RC product) is the governing circuit parameter. We select component types such that resistor temperature coefficient and drift are positive, capacitor temperature coefficient and drift negative (a condition which may be realized in practice with any of several component types). For simplicity, we use broad intervals in the value and drift histograms shown in Figures 3, 3a, 4, and 4a.

From the initial component value distribution of time constants is computed as follows:

% Nominal Resistance	% of Resistor Population	% Nominal Capacitance	% of Capacitor Population	% Nominal RC Product	% of RC Population
96	15	98	10	94.08	1.50
		100	45	96.00	6.75
		102	40	97.92	6.00
		104	5	99.84	0.75
98	35	98	10	96.04	3.50
		100	45	98.00	15 75
		102	40	99.96	14.00
		104	5	101.92	1.75

(cont.)

% Nominal Resistance	% of Resistor Population	% Nominal Capacitance	% of Capacitor Population	% Nominal RC Product	% of RC Population
100	30	98	10	98.00	3.00
		100	45	100.00	13.50
		102	40	102.00	12.00
		104	5	104.00	1.50
102	20	98	10	99.96	2.00
		100	45	102.00	9.00
		102	40	104.04	8.00
		104	5	106.08	1.00
					100.00

Rounding and summarizing the initial distribution of time constants becoming,

% Nominal RC Product	% of RC Population
94	1.50
96	10.25
98	24.75
100	30.25
102	22.75
104	9.50
106	1.00
	100.00

We now proceed to compute the resistance and capacitance distributions at the end of the desired service life (due to drift):

% Nominal Resistance (Initial)	% of Population	% of Drift	% of Population	% Nominal Resistance (final)	% of Population
96	15	0	20	96	3.00
		2	70	98	10.50
		4	10	100	1.50
98	35	0	20	98	7.00
		2	70	100	24.50
		4	10	102	3.50
100	30	0	20	100	6.00
		2	70	102	21.00
		4	10	104	3.00
102	20	0	20	102	4.00
		2	70	104	14.00
		4	10	106	2.00
					100.00

Summarizing:

% Nominal Resistance	% of Population
96	3.00
98	17.50
100	32.00

(cont.)

Summarizing:

% Nominal Resistance	% of Population
102	28.50
104	17.00
106	2.00
	100.00

And, for capacitance:

% Nominal Capacitance (Initial)	% of Population	% of Drift	% of Population	% Nominal Capacitance (final)	% of Population
98	10	-6	15	92	1.50
		-4	60	94	6.00
		-2	25	96	2.50
100	45	-6	15	94	6.75
		-4	60	96	27.00
		-2	25	98	11.25
102	40	-6	15	96	6.00
		-4	60	98	24.00
		-2	25	100	10.00
104	5	-6	15	98	0.75
		-4	60	100	3.00
		-2	25	102	1.25
					100.00

Summarizing:

% Nominal Capacitance	% of Population
92	1.50
94	12.75
96	35.50
98	36.00
100	13.00
102	1.25
	100.00

From the distributions of final values of resistance and capacitance, we compute the final distribution of time constants, this time rounding as we proceed:

% Nominal Resistance	% of Resistor Population	% Nominal Capacitance	% of Capacitance Population	% Nominal RC Product	% of RC Population
96	3.00	92	1.50	88	0.045
		94	12.75	90	0.382
		96	35.50	92	1.065
		98	36.00	94	1.080
		100	13.00	96	0.390
		102	1.25	98	0.038
98	17.50	92	1.50	90	0.262
		94	12.75	92	2.231
		96	35.50	94	6.213
		98	36.00	96	6.300
		100	13.00	98	2.275
		102	1.25	100	0.219

(cont.)

% Nominal Resistance	% of Resistor Population	% Nominal Capacitance	% of Capacitance Population	% Nominal RC Product	% of RC Population
100	32.00	92	1.50	92	0.480
		94	12.75	94	4.080
		96	35.50	96	11.360
		98	36.00	98	11.520
		100	13.00	100	4.160
		102	1.25	102	0.400
102	28.50	92	1.50	94	0.427
		94	12.75	96	3.634
		96	35.50	98	10.118
		98	36.00	100	10.260
		100	13.00	102	3.705
		102	1.25	104	0.356
104	17.00	92	1.50	96	0.255
		94	12.75	98	2.168
		96	35.50	100	6.035
		98	36.00	102	6.120
		100	13.00	104	2.210
		102	1.25	106	0.212
106	2.00	92	1.50	98	0.030
		94	12.75	100	0.255
		96	35.50	102	0.710
		98	36.00	104	0.720
		100	13.00	106	0.260
		102	1.25	108	0.025
					100.000

Summarizing and comparing with the initial distribution:

% Nominal RC Product	% of Population (Initial)*	% of Population (Final)	Change
88	0.000	0.045	0.045
90	0.000	0.644	0.644
92	0.000	3.776	3.776
94	1.500	11.800	10.300
96	10.250	21.939	11.689
98	24.750	26.149	1.399
100	30.250	20.929	-9.321
102	22.750	10.935	-11.815
104	9.500	3.286	-6.214
106	1.000	0.472	-0.528
108	0.000	0.025	0.025

* Significance of figures is apparent, not actual -- at best, significance extends only to first decimal place.

Despite the obvious and unavoidable broadening of the time constant range due to drift, it will be noted that only about 4.5% of the circuits have drifted out of the original range. By way of comparison, 19% of the resistors and nearly 50% of the capacitors have drifted out of their original ranges when they are considered independently. As discussed previously, even further improvement could be gained by reduction of initial tolerances, appropriate shifting of nominal value for procurement purposes, and trade-off of tolerances between the component types for the most economical attainment of reliability objectives.

Life test measurement data contain, when individual component part identity is maintained throughout the test, two types of information.

The first type is frequency distribution for various points in time which show the distribution of absolute values. The second type of information is frequency distributions of parameter changes for points in time. In application such as communications circuitry for example, where circuits are "trimmed" as part of the production process, the parameter changes as a function of time are of most immediate interest; in other applications, distribution of ab-

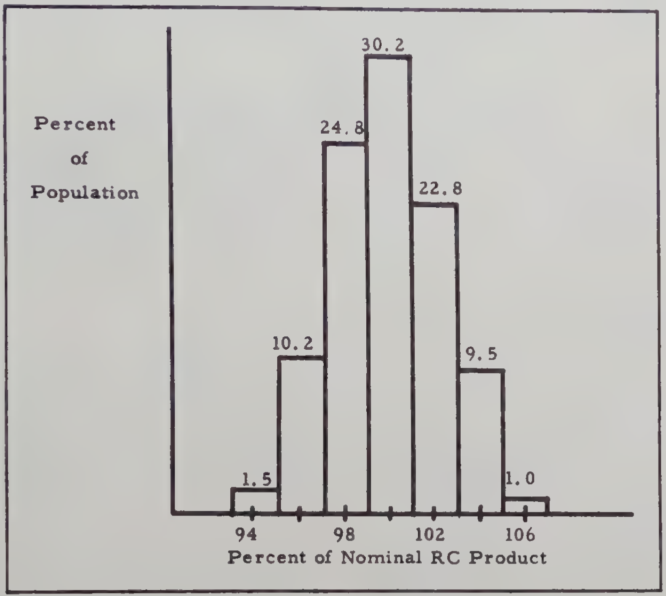


Fig. 5 - Initial distribution of time constants.

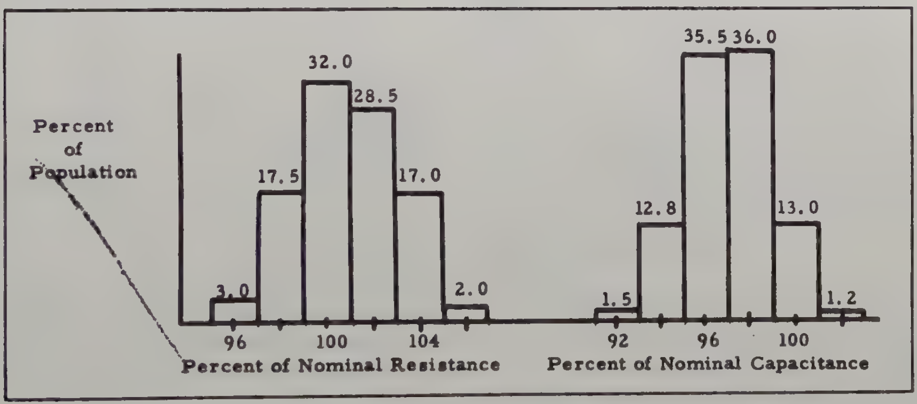


Fig. 6 - End of service life distributions of values.

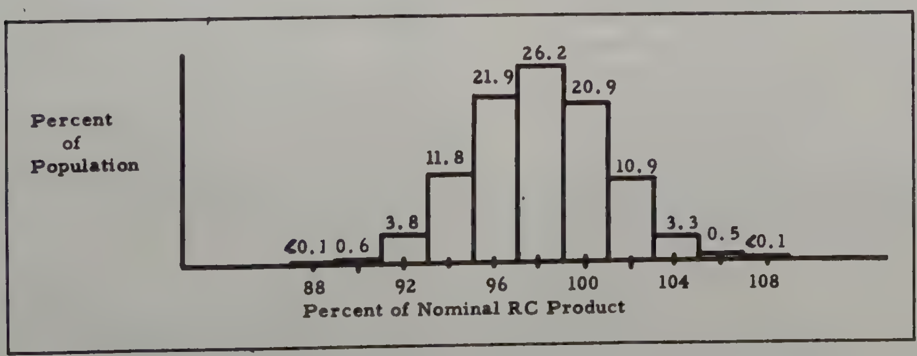


Fig. 6a - End of service life distribution of time constants.

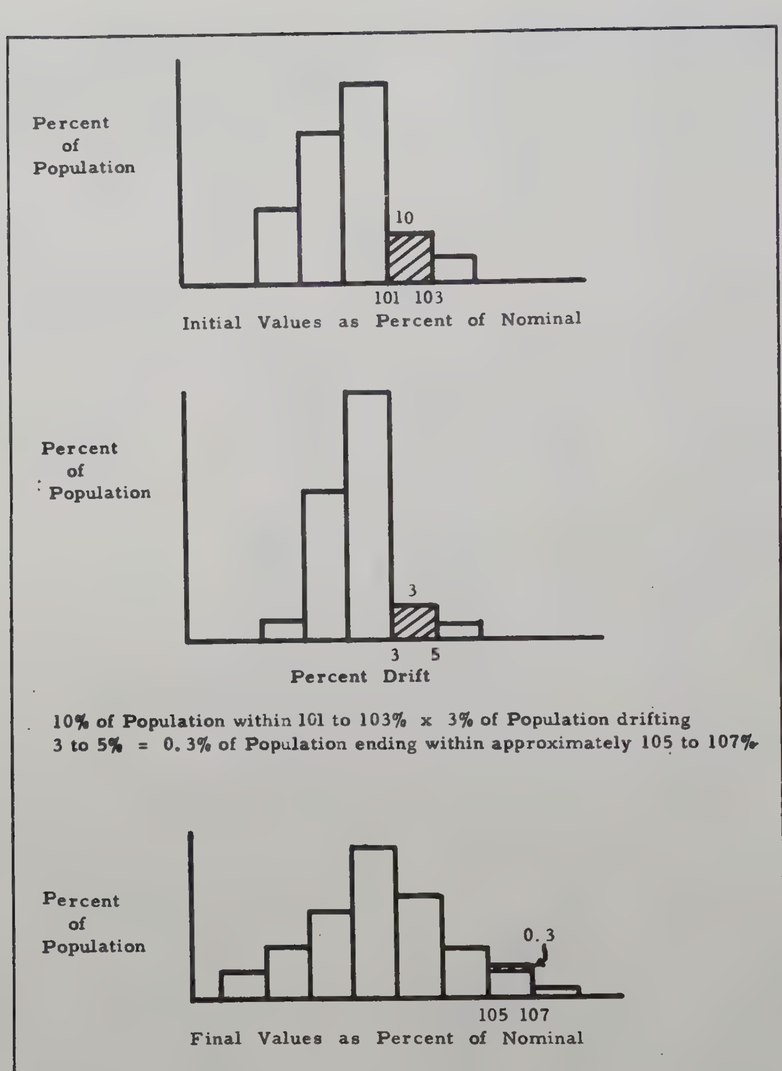


Fig. 7 - Sample computation.

solute values may be the more useful type of presentation. It should be emphasized that a data presentation that contains only absolute values as a function of time can be misleading because large changes of individual units may be masked. Our examples required both types of information. Generally, in the interests of economy of presentation, only a distribution of initial values and distributions of parameter changes as a function of time are essential since absolute value distributions may be readily derived from the change information. Any of the computations covered in this paper may be simplified where manageable frequency functions can be substituted for histograms; such functions are rarely found in practice.

As demonstrated in this paper, the technique of computation of expected distribution of parameter values at any point in time is straightforward. The designer using reliability test results must be aware of the necessity of determining initial value distributions from incoming inspection records, and of his power to change these distributions in favorable directions by basing purchasing specification requirements on circuit reliability analysis.

ADDENDUM TO THE PAPER "AN APPLICATION OF THE BOX TECHNIQUE TO THE EVALUATION OF ELECTRICAL COMPONENTS"

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Presented here are examples of the statistical analysis of the responses for two of the variables, Pulse Response Factor, and Rcs referred to in the titled paper. It is intended to show a step-by-step procedure in analyzing the results with particular emphasis placed on the details in preparing the Analysis of Variance Table.

As a preliminary step, the response for each variable was re-examined and that data which was felt to be inconsistent with the balance of the data was removed. The response equations were then recalculated, this time using the design levels (0, ±1, ±a) rather than the actual values of the independent variables. The new equations thus calculated were:

Pulse

$$\hat{Y} = -18.9 - 4.6X_1 + .3X_2 + .8X_3 + 2.6X_1^2 + 1.7X_2^2 + 3.0X_3^2 - 1.6X_1X_2 + .3X_1X_3 + 1.1X_2X_3$$

Rcs

$$\hat{Y} = 17.9 + 44.3X_1 + .4X_2 + .7X_3 + 4.4X_1^2 - 1.8X_2^2 - 1.5X_2^2 - .1X_1X_2 + .6X_1X_3 - .1X_2X_3$$

Using the design levels in these equations corresponding to the actual levels of our check point: T = 90°C (.67), V = 33 volts (.60) and P = 75 mw (.23), we get the predicted percent changes:

Pulse

= -20.1

Rcs

= 49.2

These differ slightly from those previously computed. The variance of this estimate can be obtained from the expression:

$$Var(\hat{Y}) = \sigma^2\left[\frac{1}{N} + \frac{n\cdot 2^n}{2N\,\alpha^4} + \left(\frac{2^n}{\alpha^4} - 1\right)\left(\frac{\Sigma x^4}{2^{n+1}} - \frac{\Sigma x^2}{\sqrt{n\cdot 2^n}} + \frac{(\Sigma x^2)^2}{2^{n+1}}\right)\right]$$

where n = the number of factors

$N = (2^n + 2n + k)$ points

α = the distance of the "prong" points from the centroid

The value for σ^2 taken here is the estimate of error at the center points. It is pointed out by Dr. Box that: "In cases where the variance is not constant at different points, the ordinary method of least squares applied to the mean values of the points will not provide estimates having the smallest possible variance. However, the estimates will be unbiased, and provided variances do not differ too much, will be fairly efficient."

The variances about the predicted values at the check point are:

Pulse Response	=	1.99
Rcs Response	=	.91

From this we determine that the actual value (-16.3%) for the Pulse Response lies within three sigma of the predicted value. However, the actual value of Rcs (28.2%) lies extremely far from the predicted value. A look at the analysis of variance tables for the two responses indicates why.

ANALYSIS OF VARIANCE

To obtain the analysis of variance table the following calculations must be made:

Pulse Response

A. Total sum of squares corrected for the mean with (N-1) degrees of freedom (19 in this example) =

$$\Sigma y^2 - N\left(\frac{\Sigma y}{n}\right)^2 = 649.4$$

B. Sum of squares due to regression with (N - 1 d.f. for each coefficient estimated) degrees of freedom (10) = $\Sigma y^2 - \beta' x' y$ = 144.5 (B' = row vector of betas, X' = row vector of the independent variables, and Y = the column vector for the dependent variable.)

C. Error sum of squares taken from one or more of the experimental points (k center points in this case) with (k-1) d.f. (5) =

$$\Sigma y_c^2 - k\left(\frac{\Sigma y_c}{k}\right)^2 = 31.1$$

D. Lack-of-fit sum of squares by subtraction (B-C) with (B d.f. -C d.f.) = 5d.f., this equals 113.4.

E. Linear sum of squares taken from the regression equation with one d.f. for each of the linear terms (3) $= \Sigma(b_i x_i)^2 = b_1^2 \Sigma x_1^2 + b_2^2 \Sigma x_2^2 + b_3^2 \Sigma x_3^2 = 274.5$

F. Quadratic sum of squares with (A-B-E) d.f. (6) = 230.4.

Putting this information in the analysis of variance table we get:

		d.f.	S.S.	M.S.	
	Linear	3	274.5	91.5	
	Quadratic	6	230.4	38.4	
Residual	Lack-of-fit	5	113.4	22.7	14.4 with 10 d.f.
	Error	5	31.1	6.2	
	Total	19	649.4		

From this table we see that at the 95% confidence level "lack-of-fit" is not significant. Pooling the error and lack-of-fit sums of squares and their degrees of freedom we calculate the residual error mean square. Using this in the F-test we find the quadratic terms are not significant, the implication being that a linear model might well have described the response.

If similar calculations are done on the Rcs response, the resulting table is:

		d.f.	S.S.	M.S.
	Linear	3	24,833.3	8,277.8
	Quadratic	6	259.4	43.2
Residual	Lack-of-fit	5	215.7	43.1
	Error	5	14.2	2.8
	Total	19	25,322.6	

Here we see that a definite lack-of-fit condition exists, and a closer inspection of the data is essential. One technique for doing this is to diagram the original experimental points showing the actual response and the residual at each point. These are seen in figures 1 through 4.

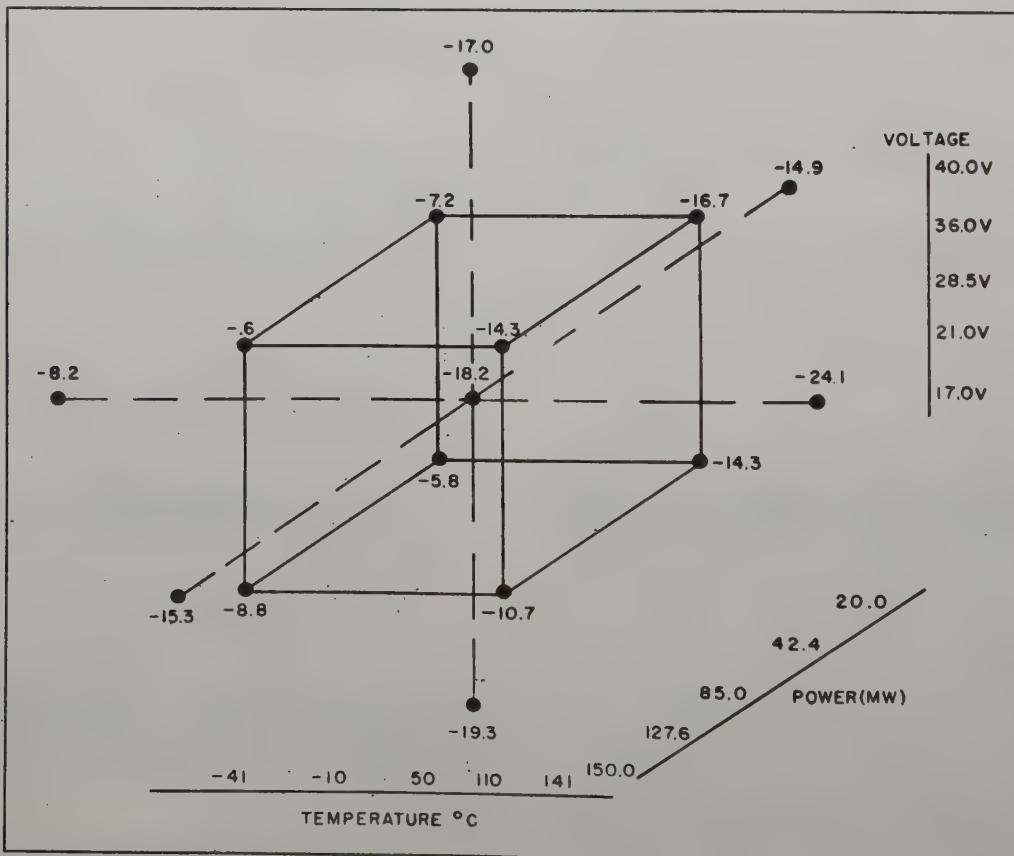

Fig. 1 -- Pulse Responses.

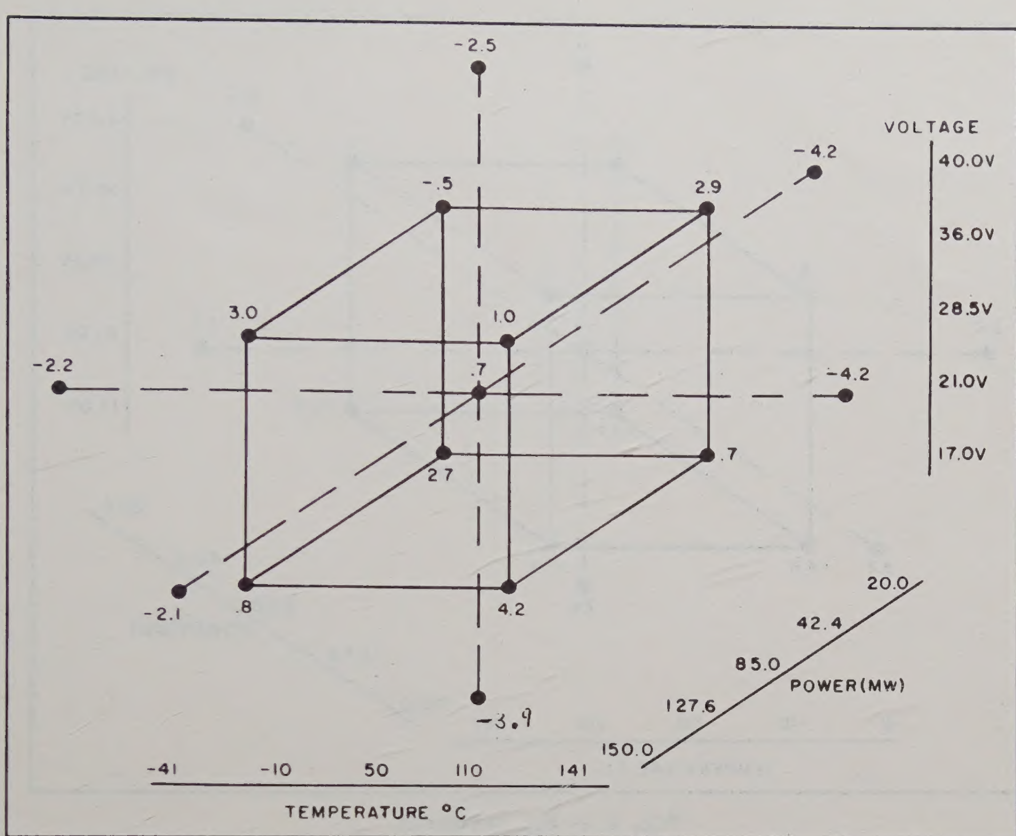

Fig. 2 -- Pulse residuals.

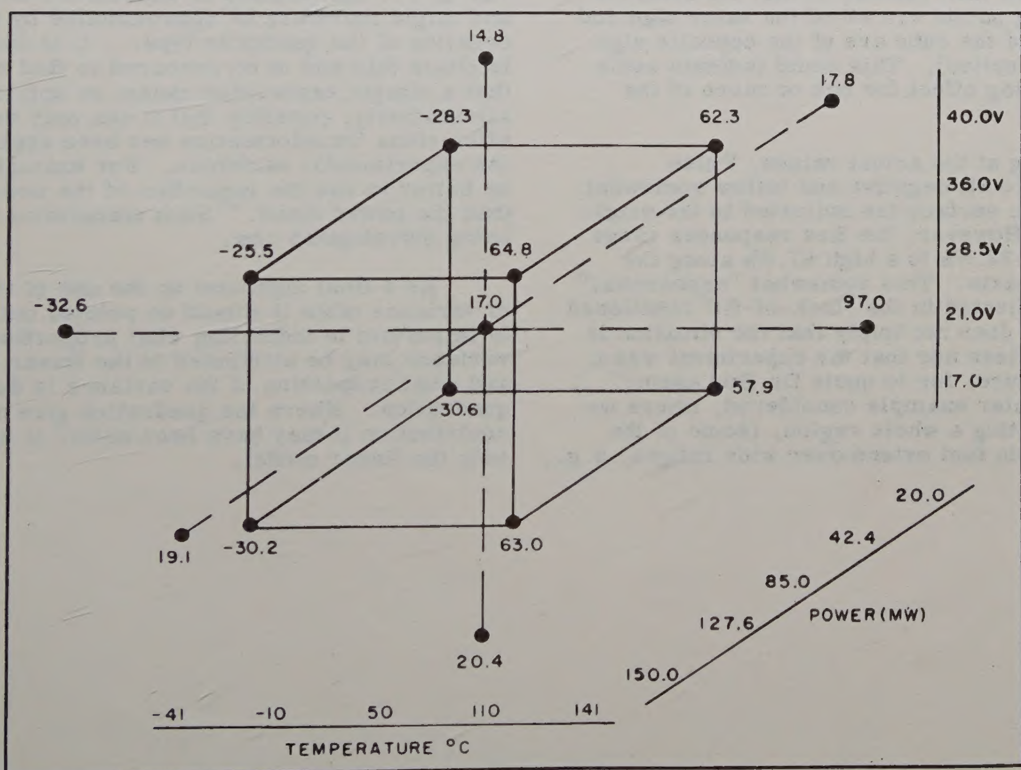

Fig. 3 -- R_{cs} responses.

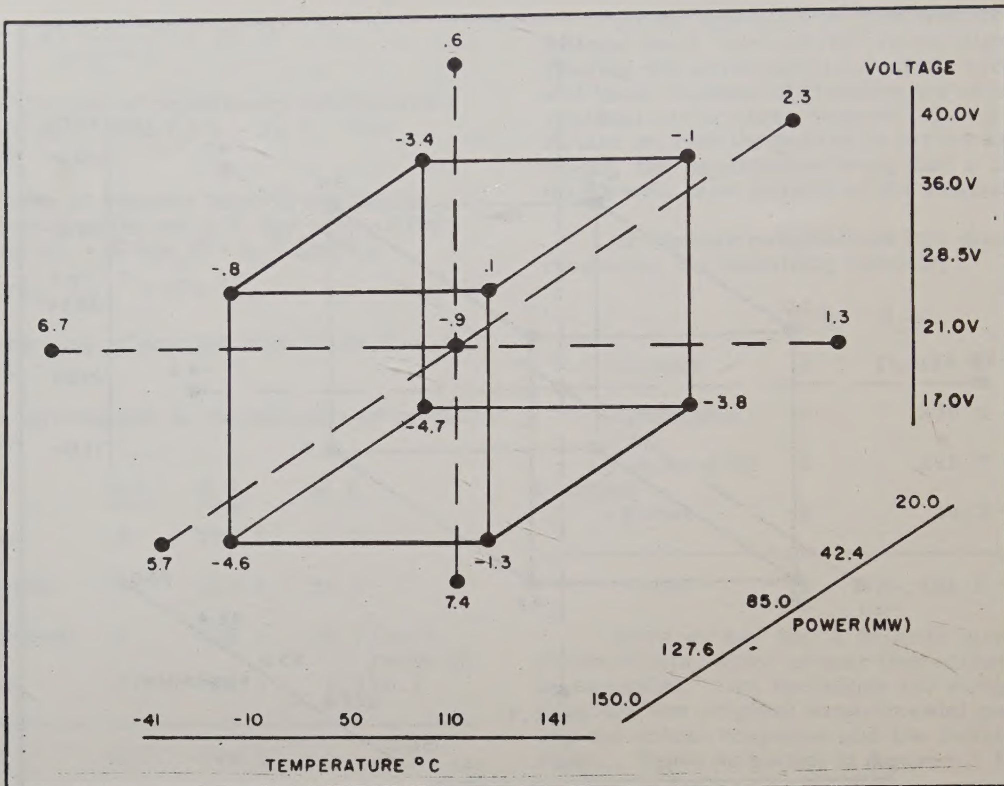

Fig. 4 -- R_{cs} residuals.

In each case, the residuals appear to be somewhat less than random in that the centroid and the prong points are all of the same sign and the corners of the cube are of the opposite sign (with one exception). This could indicate some kind of blocking effect for one or more of the variables.

Looking at the actual values, Pulse Responses are all negative and follow somewhat of a parabolic surface (as indicated in the original paper). However, the Rcs responses range from a low -32.6% to a high 97.0% along the temperature axis. This somewhat "exponential" change is reflected in the "lack-of-fit" mentioned above. This does not imply that the situation is entirely hopeless nor that the experiment was a complete failure, for to quote Dr. Box again; "... in the particular example considered, where we are investigating a whole region, (some of the variables do in fact extend over wide ranges, e.g., power 50 to 400 mw and temperature -41°C to 141°C) ... the function is expected to be smooth and might therefore be approximated by a simple equation of the quadratic type... it is important to check this and to be prepared to find either that a simple expression cannot be applied or, alternatively, possibly that it can only be applied after some transformation has been applied to the experimental variables. For example, it may be better to use the logarithm of the power rather than the power itself." Such transformations are being investigated now.

As a final comment on the use of the analysis of variance table it should be pointed out that it is important in indicating what proportion of the variance may be attributed to the linear terms, and what proportion of the variance is due to the quadratics. Where the quadratics give no marked contribution it may have been better to have used only the linear model.